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Improving multi-objective reservoir operation optimization with sensitivity-informed dimension reduction

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Abstract. This study investigates the effectiveness of a sensitivity-informed method for multi-objective operation of reservoir systems, which uses global sensitivity analysis as a screening tool to reduce computational demands. Sobol's method is used to screen insensitive decision variables and guide the formulation of the optimization problems with a significantly reduced number of decision variables. This sensitivity-informed method dramatically reduces the computational demands required for attaining high-quality approximations of optimal trade-off relationships between conflicting design objectives. The search results obtained from the reduced complexity multi-objective reservoir operation problems are then used to pre-condition the full search of the original optimization problem. In two case studies, the Dahuofang reservoir and the inter-basin multi-reservoir system in Liaoning province, China, sensitivity analysis results show that reservoir performance is strongly controlled by a small proportion of decision variables. Sensitivity-informed dimension reduction and pre-conditioning are evaluated in their ability to improve the efficiency and effectiveness of multi-objective evolutionary optimization. Overall, this study illustrates the efficiency and effectiveness of the sensitivity-informed method and the use of global sensitivity analysis to inform dimension reduction of optimization problems when solving complex multi-objective reservoir operation problems.

1 Introduction

Reservoirs are often operated considering a number of conflicting objectives (such as different water uses) related to environmental, economic, and public services. The optimization of the reservoir operation system (ROS) has attracted substantial attention over the past several decades. In China and many other countries, reservoirs are operated according to reservoir operation rule curves which are established at the planning/design stage to provide long-term operation guidelines for reservoir management to meet expected water demands. Reservoir operation rule curves usually consist of a series of storage volumes or levels at different periods (Liu et al., 2011a, b).

In order to solve the ROS problem, there are different approaches, such as implicit stochastic optimization (ISO), explicit stochastic optimization (ESO), and parameter simulation optimization (PSO) (Celeste and Billib, 2009). ISO uses deterministic optimization, e.g., dynamic programming, to determine a set of optimal releases based on the current reservoir storage and equally likely inflow scenarios (Young, 1967; Karamouz and Houck, 1982; Castelletti et al., 2012; François et al., 2014). Instead the use of equally likely inflow scenarios, ESO incorporates inflow probability directly into the optimization process, including stochastic dynamic programming and Bayesian methods (Huang et al., 1991; Tejada-Guibert et al., 1995; Powell, 2007; Goor et al., 2010; Xu et al., 2014). However, many challenges remain in application of these two approaches due to their complexity and ability to deal with conflicting objectives (Yeh, 1985; Simonovic, 1992; Wurbs, 1993; Teegavarapu and Simonovic, 2001; Labadie, 2004).

In a different way, PSO predefines a rule curve shape and then utilizes optimization algorithms to obtain the combination of rule curve parameters that provides the best reservoir operating performance under possible inflow scenarios or a long inflow series (Nalbantis and Koutsoyiannis, 1997; Oliveira and Loucks, 1997). In this way, most stochastic aspects of the problem, including spatial and temporal correlations of unregulated inflows, are implicitly included, and reservoir rule curves could be derived directly with genetic algorithms and other direct search methods (Koutsoyiannis and Economou, 2003; Labadie, 2004). Because PSO reduces the curse of dimensionality problem in ISO and ESO, it is widely used in reservoir operation optimization (Chen, 2003; Chang et al., 2005; Momtahen and Dariane, 2007). In this study, the PSO-based approach is used to solve the ROS problem.

In the PSO procedure to solve the ROS problem, the values of storage volumes or levels in reservoir operation rule curves are optimized to achieve one or more objectives directly. Quite often, there are multiple curves, related to different purposes of reservoir operation. The dimension of a ROS problem depends on the number of the curves and the number of time periods. For a cascaded reservoir system, the dimension can be very large, which increases the complexity and problem difficulty and poses a significant challenge for most search tools currently available (Labadie, 2004; Draper and Lund, 2004; Sadegh et al., 2010; Zhao et al., 2014).

In the context of multi-objective optimal operation of a ROS, there is not one single operating policy that improves simultaneously all the objectives and a set of non-dominating Pareto-optimal solutions are normally obtained. The traditional approach to multi-objective optimal reservoir operation is to reformulate the multi-objective problem as a single-objective problem through the use of some scalarization methods, such as the weighted sum method (Tu et al., 2003, 2008; Shiau, 2011). This method has been developed to repeatedly solve the single-objective problem using different sets of weights so that a set of Pareto-optimal solutions to the original multi-objective problem could be obtained (Srinivasan and Philipose, 1998; Shiau and Lee, 2005). Another well-known method is the ε-constraint method (Ko et al., 1997; Mousavi and Ramamurthy, 2000; Shirangi et al., 2008): all the objectives but one are converted into constraints and the level of satisfaction of the constraints is optimized to obtain a set of Pareto-optimal solutions. However, with the increase in problem complexity (i.e., the number of objectives or decision variables), both approaches become inefficient and ineffective in deriving the Pareto-optimal solutions.

In the last several decades, bio-inspired algorithms and tools have been developed to directly solve multi-objective optimization problems by simultaneously handling all the objectives (Nicklow et al., 2010). In particular, multi-objective evolutionary algorithms (MOEAs) have been increasingly applied to the optimal reservoir operation problems, with the intent of revealing trade-off relationships between conflicting objectives. Suen and Eheart (2006) used the non-dominated sorting genetic algorithm (NSGAII) to find the Pareto set of operating rules that provides decision makers with the optimal trade-off between human demands and ecological flow requirements. H. F. Zhang et al. (2013) used a multi-objective adaptive differential evolution combined with chaotic neural networks to provide optimal trade-offs for multi-objective long-term reservoir operation problems, balancing hydro-power operation and the requirement of a reservoir ecological environment. Chang et al. (2013) used an adjustable particle swarm optimization – genetic algorithm hybrid algorithm to minimize water shortages and maximize hydro-power production in management of Tao River water resources.

However, significant challenges remain for using MOEAs in large, real-world ROS applications. The high dimensionality of ROS problems makes it very difficult for MOEAs to identify "optimal or near-optimal" solutions with the computing resources that are typically available in practice. Thus, the primary aim of this study is to investigate the effectiveness of a sensitivity-informed optimization methodology for multi-objective reservoir operation, which uses sensitivity analysis results to reduce the dimension of the optimization problems, and thus improves the search efficiency in solving these problems. This framework is based on the previous study by Fu et al. (2012), which developed a framework for dimension reduction of optimization problems that can dramatically reduce the computational demands required to obtain high-quality solutions for optimal design of water distribution systems. The ROS case studies used to demonstrate this framework consider the optimal design of reservoir water supply operation policies. Storage volumes at different time periods on the operation rule curves are used as decision variables. It has been widely recognized that the determination of these decision variables requires a balance among different ROS objectives. Sobol's sensitivity analysis results are used to form simplified optimization problems considering a small number of sensitive decision variables, which can be solved with a dramatically reduced number of model evaluations to obtain Pareto-approximate solutions. These Pareto-approximate solutions are then used to pre-condition a full search by serving as starting points for the multi-objective evolutionary algorithm. The results from the Dahuofang reservoir and inter-basin multi-reservoir system case studies in Liaoning province, China, whose conflicting objectives are minimization of industry water shortage and minimization of agriculture water shortage, illustrate that sensitivity-informed dimension reduction and pre-conditioning provide clear advantages to solve large-scale multi-objective ROS problems effectively.

2 Problem formulation

Most reservoirs in China are operated according to rule curves, i.e., reservoir water supply operation rule curves. Since they are based on actual water storage volumes, they are simple to use. Figure 1 shows an illustration of rule curves for Dahuofang reservoir based on 36 10-day periods.

As we know, water demand can be fully satisfied only when there is sufficient water in the reservoir. The water supply operation rule curve, which is used to operate most reservoirs in China, represents the limited storage volume for water supply in each period of a year. In detail, water demand will be fully satisfied when the reservoir storage volume is higher than the water supply operation rule curve; conversely, water demand needs to be rationed when the reservoir storage volume is lower than the water supply operation rule curve. In general, a reservoir has more than one water supply target, and there is one to one correspondence between water supply rule curve and water supply target. The water supply with lower priority will be limited prior to the water supply with higher priority when the reservoir storage volume is not sufficient. To reflect the phenomenon that different water demands can have different reliability requirements and thus different levels of priority in practice, the operation rule curve for the water supply with the lower priority is located above the operation rule curve for the water supply with the higher priority.

Figure 1 shows water supply operation rule curves for agriculture and industry where the maximum storage is smaller in the middle due to the flood control requirements in wet seasons. In Fig. 1, the red line with circles represents the water supply rule curve for agriculture, the green line with triangles represents the water supply rule curve for industry. The water supply rule curve for agriculture with lower priority is located above the water supply rule curve for industry with higher priority. The water storage available between the minimum and maximum storages is divided into three parts: zone 1, zone 2, and zone 3 by the water supply rule curves for agriculture and industry.

Specifically, both the agricultural demand D_1 and the industrial demand D_2 could be fully satisfied when the actual water storage is in zone 1, which is above the water supply rule curve for agriculture. When the actual water storage is in zone 2, the industrial demand could be fully satisfied, and the agricultural demand has to be rationed. Both the agricultural demand and the industrial demand have to be rationed when the actual water storage is in zone 3. The water supply rule for a specific water user consists of one water supply rule curve and rationing factors that indicate the reliability and priority of the water user. The rationing factors used to determine the amount of water supply for different water demands can be either assigned according to the experts' knowledge or determined by optimization (Shih and ReVelle, 1995). In this paper, rationing factors are given at the reservoir's design stage according to the tolerable elastic range of each water

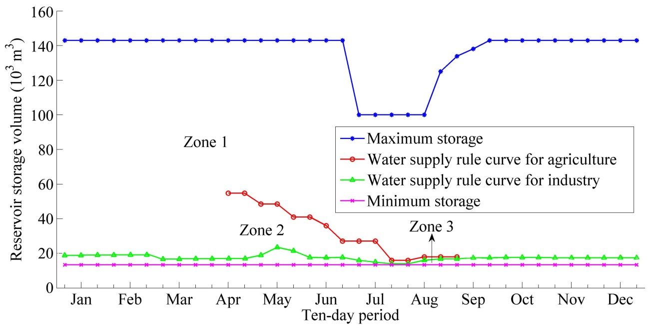

Figure 1. Reservoir operational rule curves.

user in which the damage caused by rationing water supply is limited. Assuming that the specified water rationing factor α_1 is applied to the water supply rule curve for agriculture in Fig. 1, the agricultural demand D_1 could be fully supplied without rationing when the actual water storage is in zone 1; however, when the water storage is in zone 2 or zone 3, the agricultural demand has to be rationed, i.e., $\alpha_1 \times D_1$. Similarly, assuming that the specified water rationing factor α_2 is applied to the water supply rule curve for industry in Fig. 1, the industrial demand D_2 could be fully supplied without rationing when the actual water storage is in zone 1 or zone 2; however, when the water storage is in zone 3, the industrial demand has to be rationed, i.e., $\alpha_2 \times D_2$.

To provide long-term operation guidelines for reservoir management for meeting expected water demands for future planning years, the projected water demands and long-term historical inflow are used. The optimization objective for water supply operation rule curves is to minimize water shortages during the long-term historical period. The ROS design problem is formulated as a multi-objective optimization problem, i.e., minimizing multiple objectives simultaneously. In this paper, the objectives are to minimize industry and agriculture water shortages:

$$\min f_i(\boldsymbol{x}) = \mathrm{SI}_i = \frac{100}{N} \sum_{j=1}^{N} \left(\frac{D_{i,j} - W_{i,j}(\boldsymbol{x})}{D_{i,j}} \right)^2, \quad (1)$$

where $\boldsymbol{x}$ is the vector of decision variables, i.e., the water storages at different periods on a water supply rule curve; SI_i is the shortage index for water demand i (agricultural water demand when $i=1$, industrial water demand when $i=2$), which measures the average annual shortage occurred during N years, and is used as an indicator to reflect water supply efficiency; N is the total number of years simulated; $D_{i,j}$ is the demand for water demand i during the jth year; and $W_{i,j}(x)$ is the actually delivered water for water demand i during the jth year. The term $W_{i,j}(x)$ is calculated below using agricultural water demand ($i=1$) as an example. If the actual water storage is above the water supply rule curve for agricultural water demand ($i=1$) at period t in a year, the delivered water at period t is its full demand without being rationed, $D_{1,t}$. If the actual water storage is below the water supply rule curve for agricultural water demand at period t, the delivered water for agricultural water demand at period t is its rationed demands, $\alpha_1 \times D_{1,t}$.

For the ROS optimization problem, the mass balance equations are

$$S_{t+1} - S_t = I_t - R_t - SU_t - E_t, \tag{2}$$

$$R_t = g(\boldsymbol{x}), \quad \mathrm{SU}_t = k(\boldsymbol{x}), \quad E_t = e(\boldsymbol{x}), \tag{3}$$

$$\mathrm{ST}_t^{\min} \le S_t \le ST_t^{\max}, \quad \mathrm{ST}_t^{\min} \le \boldsymbol{x} \le \mathrm{ST}_t^{\max}, \tag{4}$$

where S_t is the initial water storage at the beginning of period t; S_{t+1} is the ending water storage at the end of period t; I_t, R_t, SU_t, and E_t are inflow, delivery for water use, spill and evapotranspiration loss, respectively; and $\mathrm{ST}_t^{\max}$ and $\mathrm{ST}_t^{\min}$ are the maximum and minimum storage, respectively. Additionally, because $W_{i,j}(x)$ in Eq. (1) is the actually delivered water for water demand i during the jth year, R in that year is equal to the sum: $W_{1,j}(x) + W_{2,j}(x)$.

3 Methodology

Pre-conditioning is a technique that uses a set of known good solutions as starting points to improve the search process of optimization problems (Nicklow et al., 2010). It is very challenging to determine good initial solutions, and different techniques including the domain knowledge can be used. This study utilizes a sensitivity-informed dimension reduction to develop simpler search problems that consider only a small number of highly sensitive decisions. The results from these simplified search problems can be used to successively pre-condition the search for larger, more complex formulations of ROS design problems. The ε-NSGAII, a popular multi-objective evolutionary algorithm, is chosen as it has been shown to be effective for many engineering optimization problems (Kollat and Reed, 2006; Tang et al., 2006; Kollat and Reed, 2007). For the two objectives considered in this paper, their epsilon values in ε-NSGAII ($\varepsilon_{\mathrm{SI}_1}$ and $\varepsilon_{\mathrm{SI}_2}$) were chosen based on reasonable and practical requirements and were both set to 0.01. According to the study by Fu et al. (2012), the sensitivity-informed methodology, as shown in Fig. 2, has the following steps:

1. Perform a sensitivity analysis using Sobol's method to calculate the sensitivity indices of all decision variables regarding the ROS performance measure.

2. Define a simplified problem that considers only the most sensitive decision variables by imposing a user specified threshold (or classification) of sensitivity.

3. Solve the simplified problem using ε-NSGAII with a small number of model simulations.

4. Solve the original problem using ε-NSGAII with the Pareto-optimal solutions from the simplified problem fed into the initial population.

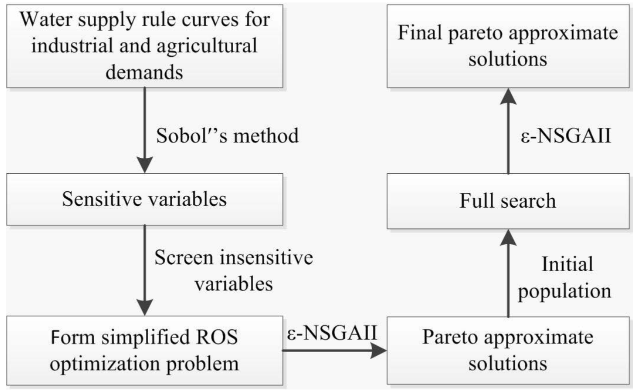

Figure 2. Flowchart of the sensitivity-informed methodology.

3.1 Sobol's sensitivity analysis

Sobol's method was chosen for sensitivity analysis because it can provide a detailed description of how individual variables and their interactions impact model performance (Tang et al., 2007b; C. Zhang et al., 2013). A model could be represented in the following functional form:

$$y = f(\boldsymbol{x}) = f\left(x_1, \cdots, x_p\right), \tag{5}$$

where y is the goodness-of-fit metric of model output, and $\boldsymbol{x} = \left(x_1, \cdots, x_p\right)$ is the parameter set. Sobol's method is a variance-based method, in which the total variance of model output, $D(y)$, is decomposed into component variances from individual variables and their interactions:

$$D(y) = \sum_i D_i + \sum_{i<j} D_{ij} + \sum_{i<j<k} D_{ijk} + \cdots + D_{12\cdots m}, \tag{6}$$

where D_i is the amount of variance due to the ith variable x_i, and D_{ij} is the amount of variance from the interaction between x_i and x_j. The model sensitivity resulting from each variable can be measured using the Sobol's sensitivity indices of different orders:

$$\text{First-order index:} \quad S_i = \frac{D_i}{D}, \tag{7}$$

$$\text{Second-order index:} \quad S_{ij} = \frac{D_{ij}}{D}, \tag{8}$$

$$\text{Total-order index:} \quad S_{Ti} = 1 - \frac{D_{\sim i}}{D}, \tag{9}$$

where $D_{\sim i}$ is the amount of variance from all the variables except for x_i, the first-order index S_i measures the sensitivity from the main effect of x_i, the second-order index S_{ij} measures the sensitivity resulting from the interactions between x_i and x_j, and the total-order index S_{Ti} represents the main effect of x_i and its interactions with all the other variables.

3.2 Performance metrics

Since an MOEA uses random-based search, performance metrics are used in this study to compare the quality of

Table 1. Reservoir characteristics and yearly average inflow (10^6 m^3).

Reservoir name	Minimum capacity	Utilizable capacity	Flood control capacity	Yearly average inflow
Dahuofang	134	1430	1000	1570

the approximation sets derived from replicate multi-objective evolutionary algorithm runs. Three indicators were selected: the generational distance (Veldhuizen and Lamont, 1998), the additive ε-indicator (Zitzler et al., 2003), and the hypervolume indicator (Zitzler and Thiele, 1998).

The generational distance measures the average Euclidean distance from solutions in an approximation set to the nearest solution in the reference set, and indicates perfect performance with zero. The additive ε-indicator measures the smallest distance that a solution set needs to be translated to completely dominate the reference set. Again, smaller values of this indicator are desirable as this indicates a closer approximation to the reference set.

The hypervolume indicator, also known as the S metric or the Lebesgue measure, measures the size of the region of objective space dominated by a set of solutions. The hypervolume not only indicates the closeness of the solutions to the optimal set but also captures the spread of the solutions over the objective space. The indicator is normally calculated as the volume difference between a solution set derived from an optimization algorithm and a base solution set. In this study, the worst case solution is chosen as base. For example, the worst solution is (1, 1) for two minimization objectives in the normalized objective space. Thus, larger hypervolume indicator values indicate improved solution quality and imply a larger distance from the worst solution.

4 Case study

Two case studies of increasing complexity are used to demonstrate the advantages of the sensitivity-informed methodology: (1) the Dahuofang reservoir, and (2) the inter-basin multi-reservoir system in Liaoning province, China. The inter-basin multi-reservoir system test case is a more complex ROS problem with the Dahuofang, Guanyinge, and Shenwo reservoirs. In the two ROS problems, the reference sets were obtained from all the Pareto-optimal solutions across a total of 10 random seed trials, each of which was run for a maximum number of function evaluations (NFEs) of 500 000. Additionally, the industrial and agricultural water demands in the future planning year, i.e., 2030, and the historical inflow from 1956 to 2006 were used to optimize reservoir operation and meet future expected water demands in the two case studies.

4.1 Dahuofang reservoir

The Dahuofang reservoir is located in the main stream of Hun River, in Liaoning province, northeast China. The Dahuofang reservoir basin drains an area of 5437 km^2, and within the basin the total length of Hun River is approximately 169 km. The main purposes of the Dahuofang reservoir are industrial water supply and agricultural water supply to central cities in Liaoning province. The reservoir characteristics and yearly average inflow are illustrated in Table 1.

The Dahuofang ROS problem is formulated as follows: the objectives are minimization of industrial shortage index and minimization of agricultural shortage index as described in Eq. (1); the decision variables include storage volumes on the industrial and agricultural curves. For the industrial curve, a year is divided into 24 time periods (with 10 days as the scheduling time step from April to September, and 1 month as the scheduling time step in the remaining months). Thus, there are 24 decision variables for industrial water supply. The agricultural water supply occurs only in the periods from the second 10 days of April to the first 10 days of September; thus, there are 15 decision variables for agricultural water supply. In total, there are 39 decision variables.

4.2 Inter-basin multi-reservoir system

As shown in Fig. 3, the Dahuofang, Guanyinge, and Shenwo reservoirs compose the inter-basin multi-reservoir system in Liaoning province, China.

Liaoning province in China covers an area of 146×10^3 km^2 with an extremely uneven distribution of rainfall in space. The average amount of annual precipitation decreases from 1100 mm in the east to 600 mm in the west (MWR-PRC, 2008). However, the population, industries, and agricultural areas are mainly concentrated in the western parts. Therefore, it is critical to develop the best water supply rules for the inter-basin multi-reservoir system to decrease the risk of water shortages caused by the mismatch of water supplies and water demands in both water deficit regions and water surplus regions. Developing inter-basin multi-reservoir water supply operation rules has been promoted as a long-term strategy for Liaoning province to meet the increasing water demands in water shortage areas. In the inter-basin multi-reservoir system of Liaoning province, the abundant water in Dahuofang, Guanyinge, and Shenwo reservoirs is diverted downstream to meet the water demands in water shortage ar-

Table 2. Characteristics of each reservoir in the inter-basin multi-reservoir system.

Reservoir	Active storage (10^6 m^3)		Role in water
	Flood season	Non-flood season	supply project
Dahuofang	1000	1430	Supplying water
Guanyinge	1420	1420	Supplying water and exporting water to Shenwo
Shenwo	214	543	Supplying water and importing water from Guanyinge

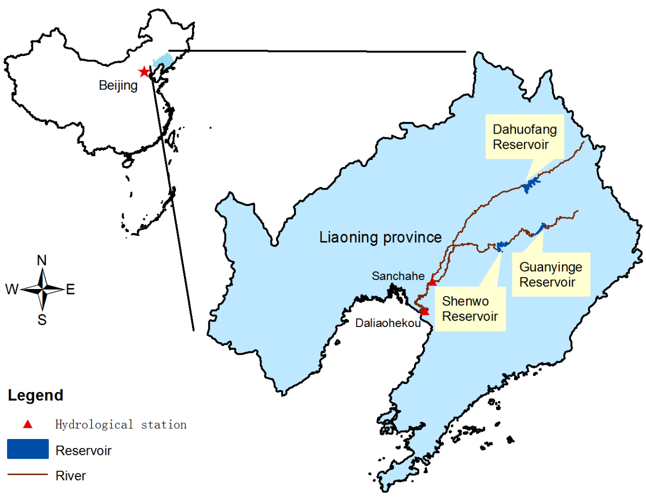

Figure 3. Layout of the inter-basin multi-reservoir system.

eas, especially in the region between Daliaohekou and Sanhekou hydrological stations.

The main purposes of the inter-basin multi-reservoir system are industrial water supply and agricultural water supply to eight cities (Shenyang, Fushun, Anshan, Liaoyang, Panjin, Yingkou, Benxi, and Dalian) of Liaoning province, and environmental water demands need to be satisfied fully. The characteristics of each reservoir in the inter-basin multi-reservoir system are illustrated in Table 2.

The flood season runs from July to September, during which the inflow takes up a large part of the annual inflow. The active storage capacities of Dahuofang and Shenwo reservoirs reduce significantly during flood season for the flood control.

The inter-basin multi-reservoir operation system problem is formulated as follows: the objectives are minimization of industrial shortage index and minimization of agricultural shortage index as described in Eq. (1). With regard to the Shenwo reservoir, which has the same water supply operation rule curve features as Dahuofang reservoir, the decision variables include storage volumes on the industrial and agricultural curves and there are 39 decision variables. Regarding Guanyinge reservoir, the decision variables include storage volumes on the industrial curve and water transferring curve due to the requirement of exporting water from Guanyinge reservoir to Shenwo reservoir in the inter-basin multi-reservoir system, which is similar to the water supply operation rule curve for industrial water demand, and there are 48 decision variables. Therefore, the inter-basin multi-reservoir system has six rule curves and $39 \times 2 + 48 = 126$ decision variables in total.

5 Results and discussions

5.1 Dahuofang reservoir

In the Dahuofang reservoir case study, a set of 2000 Latin hypercube samples were used per decision variable yielding a total number of $2000 \times (39 + 2) = 82\,000$ model simulations used to compute Sobol's indices. Following the recommendations of Tang et al. (2007a, b) boot strapping the Sobol indices showed that 2000 samples per decision variable were sufficient to attain stable rankings of global sensitivity.

The first-order indices representing the individual contributions of each variable to the variance of the objectives are shown in blue in Fig. 4. The total-order indices representing individual and interactive impacts on the variance of the objectives are represented by the total height of bars. Agr4_2 represents the decision variable responding to water storage volume on the agricultural curve at the second 10 days of April and ind3_3 represents the decision variable responding to water storage volume on the industrial curve at the last 10 days of March, and so on. Considering the shortage index for the industrial water demand, the water storages at time periods ind1, ind2, ind3, ind10, ind11, and ind12, i.e., the water storages at time periods 1, 2, 3, 10, 11, and 12 of water supply operation rule curves for industrial water demand are the most sensitive variables, accounting for almost 100 % of the total variance. Considering the agricultural shortage index, the water storages at time periods from agr4-2 to agr5-3, i.e., the water storages at the first five time periods of water supply operation rule curves for agricultural water demand, are the most sensitive variables. The explanation for the most

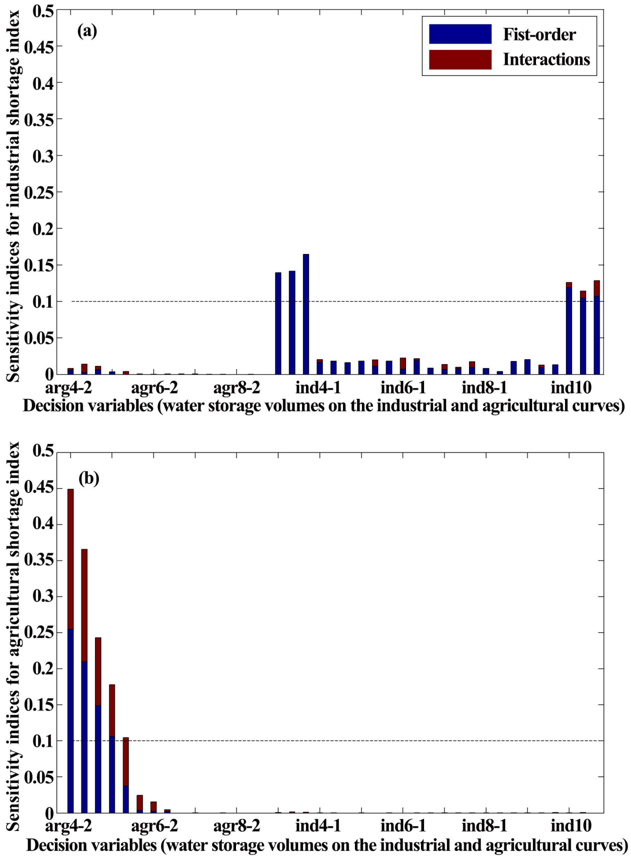

Figure 4. First-order and total-order indices for the Dahuofang ROS problem regarding **(a)** industrial shortage index and **(b)** agricultural shortage index. The x axis labels represent decision variables (water storage volumes on the industrial and agricultural curves).

sensitive variables in water supply operation rule curves for industrial and agricultural water demands will be provided in Sect. 5.1.3.

5.1.1 Simplified problems

Building on the sensitivity results shown in Fig. 4, one simplified version of the Dahuofang ROS problem is formulated: only 11 periods are considered for optimization, i.e., time periods ind1, ind2, ind3, ind10, ind11, and ind12 for industrial curve and agr4-2, agr4-3, agr5-1, agr5-2, and agr5-3 for agricultural curve based on a total-order Sobol's index threshold of greater than 10 %. The threshold is subjective and its ease-of-satisfaction decreases with increasing number of parameters or parameter interactions. In all of the results for the Sobol's method, parameters classified as the most sensitive contribute, on average, at least 10 percent of the overall model variance (Tang et al., 2007a, b). The full-search 39-period problem serves as the performance baseline relative to the reduced complexity problem.

5.1.2 Pre-conditioned optimization

In this section, the pre-conditioning methodology is demonstrated using the 11-period simplification of the Dahuofang ROS test case from the prior section, while the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem.

Using the sensitivity-informed methodology, the 11-period case was first solved using ε-NSGAII with a maximum NFEs of 2000, and the Pareto-optimal solutions combined with the constant insensitive decision variables were then used as starting points to start a complete new search with a maximum NFEs of 498 000. The standard search using ε-NSGAII was set to a maximum NFEs of 500 000, so that the two methods have the same NFEs used for search. In this case, 10 random seed trials were used given the computing resources available. The search traces in Fig. 5 show for all three metrics (generational distance, additive epsilon indicator, and hypervolume) that the complexity-reduced case can reliably approximate their portions of the industrial and agricultural water shortage trade-off given their dramatically reduced search periods. All three metrics show diminishing values at the end of the reduced search periods. The pre-conditioning results are shown in Fig. 5 in red search traces continuing from the blue reduced complexity search results.

Figure 5 clearly highlights that the sensitivity-informed pre-condition problems dramatically enhance search efficiency in terms of the generational distance, additive epsilon indicator, and hypervolume metrics. Overall, sensitivity-informed dimension reduction and pre-conditioning yield strong efficiency gains and a more reliable search (i.e., narrower band widths on search traces) for the Dahuofang ROS test case.

Figure 6a shows Pareto fronts from a NFEs of 3000, 5000, and 8000 in the evolution process of one random seed trial. In the case of the pre-conditioned search, the solutions from 3000, 5000, and 8000 evaluations are much better than the corresponding solutions in the case of standard baseline search. The results show that the Pareto-approximate front of the pre-conditioned search is much wider than that of the standard search, and clearly dominates that of the standard search in all the regions across the entire-objective space.

Figure 6b shows the best and worst Pareto fronts from a NFEs of 500 000 and 8000 in the evolution process of 10 seed trials. In the case of the pre-conditioned search, the best solutions from 500 000 evaluations are better than the corresponding solutions in the case of standard baseline search. Although it is obvious that there are not many differences between solutions obtained from pre-conditioned search and solutions from standard baseline search due to the complexity of the problem, the best Pareto fronts from a NFEs of 8000 in the case of the pre-condition search are approximately the same as the best Pareto fronts from a NFEs of 500 000 in the case of the standard baseline search.

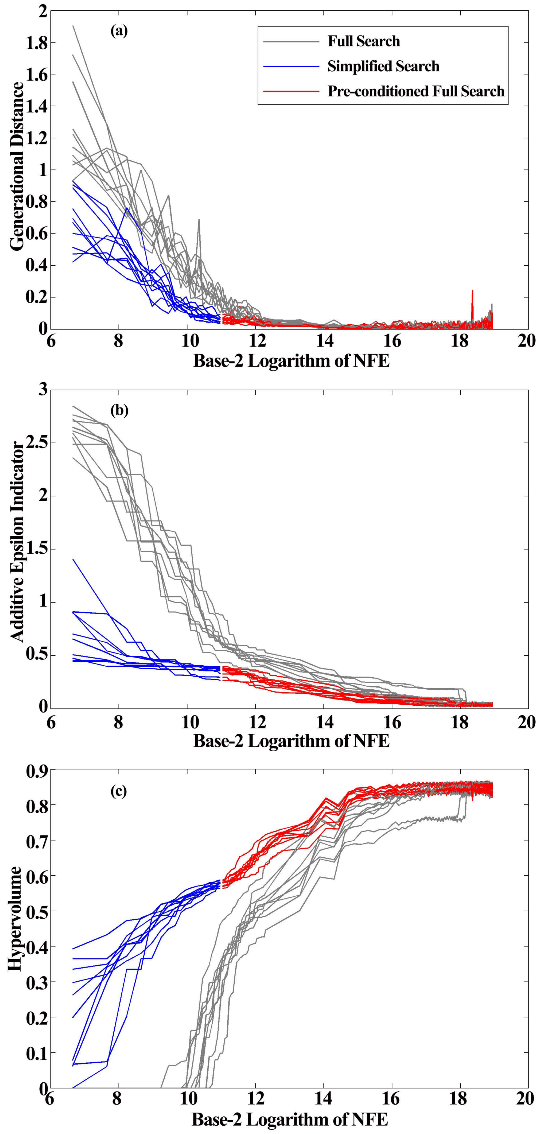

Figure 5. Performance metrics for the Dahuofang ROS problem – **(a)** generational distance, **(b)** additive epsilon indicator, and **(c)** hypervolume.

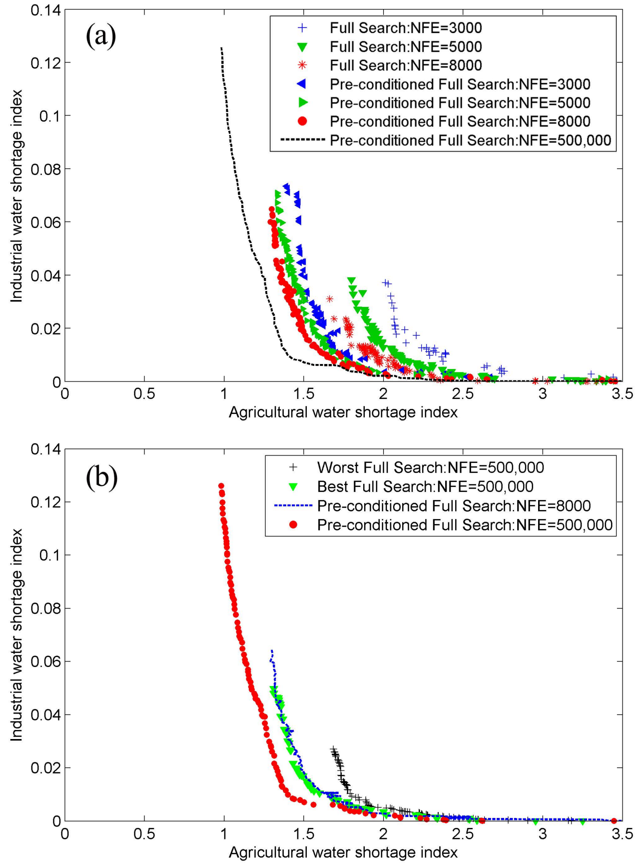

Figure 6. Pareto fronts derived from pre-conditioned and standard full searches for the Dahuofang ROS problem. **(a)** Sample Pareto fronts with different numbers of function evaluations for one random seed trial. **(b)** The best and worst Pareto fronts of 10 seed trials.

Figure 7 shows the computational savings for two thresholds of hypervolume values 0.80 and 0.85 in the evolution process of each seed trial. In both cases of the thresholds of hypervolume values 0.80 and 0.85, NFEs of the pre-conditioned search is less than standard baseline search for each seed. In the case of the threshold of hypervolume value 0.80, the average NFEs of full search and pre-conditioned full search are approximately 94 564 and 25 083 for one seed run, respectively, and the computation is saved by 73.48 %. Although the NFEs of Sobol's analysis are 82 000, the average NFEs of pre-conditioned full search is approximately 25 083 + 82 000 / 10 = 33 283 for each seed run, and the computational saving is 64.80 %.

Similarly, in the case of the threshold of hypervolume value 0.85, which is extremely difficult to achieve, the average NFEs of full search and pre-conditioned full search are approximately 214 049 and 105 060 for each seed run, respectively, and the computation is saved by 50.92 %. When the computation demand by Sobol's analysis is considered, the computational saving is still 47.09 %.

5.1.3 Optimal operation rule curves

The rule curves for Dahuofang reservoir from the final Pareto fronts based on the projected water demands and long-term historical inflow are shown in Fig. 8 (S2). The effectiveness and reasonability of the rule curves for Dahuofang reservoir are analyzed as follows.

First, the optimal operational rule curves in Fig. 8 (S2) have the same characteristics as they are used in practice. During the pre-flood season (from April to June), the curves gradually become lower so that they can reduce the probability of limiting water supply and empty the reservoir storage for the flood season (from July to early September). Dur-

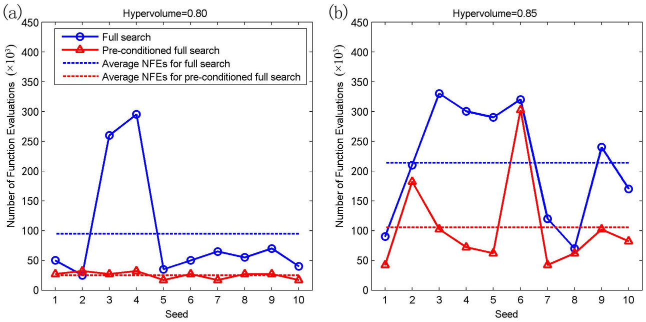

Figure 7. Computational savings for two hypervolume values – **(a)** hypervolume = 0.80 and **(b)** hypervolume = 0.85.

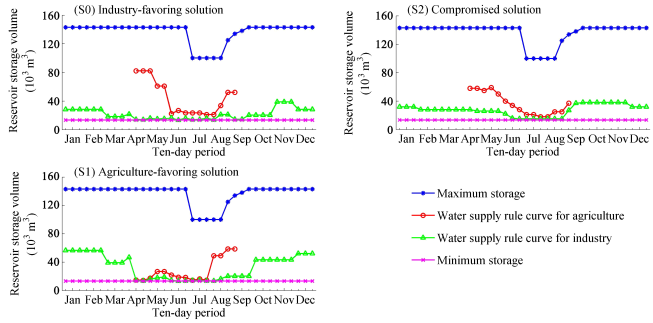

Figure 8. Optimal rule curves for different solutions: (S0) industry-favouring solution, (S1) agriculture-favouring solution, and (S2) compromised solution.

ing the flood season, the curves also stay in low positions owing to the massive reservoir inflow and the requirement of flood control, so that it is beneficial to supply as much water as possible. However, during the season from mid-September to March, the curves remain high, especially from mid-September to October, in order to increase the probability of limiting water supply and retaining enough water for later periods to avoid severe water supply shortages as drought occurs.

Second, Fig. 8 (S2) shows that different water demands occur at different periods; e.g., industrial water demand occurs throughout the whole year, and agricultural water demand occurs only at the periods from the second 10 days of April to the first 10 days of September. Especially during the flood season, there are still agricultural water demands due to temporal and spatial variations of rainfall though they are significantly reduced. Furthermore, note that the water supply curves are developed based on a historical, long-term rainfall series and the projected demands are also based on historical demands, covering stochastic uncertainties in demands and rainfalls. Due to the higher priority of industrial water supply than agricultural water supply, the industrial water supply curve is closer to minimum storage throughout the year than the agricultural water supply curve. Due to the conflicting relationship between industrial and agricultural water demands, the industrial water supply curve is higher during the non-flood season, compared to the same curve in the flooding season. Thus, if the industrial water supply curve is too low during the non-flood season from January to April, which implies that the industrial water demand is satisfied sufficiently, there would not be enough water supplied for the agricultural water demand in the same year. Similarly, if the industrial water supply curve is too low during the non-flood season from September to December, there would not be enough water supplied for the agricultural water demand in the next 1 or more years.

Third, the inflow and industrial water demands are relatively stable during the non-flood seasons from January to March and from October to December, so 1 month is taken as the scheduling time step, which is in accordance with the requirement of Dahuofang reservoir operation in practice. Due to the larger amount of industrial water demand in periods 1, 2, 3, 10, 11, and 12 (January–March and October–December) than other periods, the water storages at these time periods are very important to industrial water supply, making them the most sensitive variables. Because the agricultural water demand is very high during the non-flood period from April to May, the agricultural water supply curve at this time period is higher, and the water storages at time periods from agr4-2 to agr5-3, i.e., the water storages at the first five time periods of the water supply operation rule curve for agricultural water demand, are the most important variables. On the other hand, in practice, if the agricultural water demand could not be satisfied at the first few periods of the water supply operation rule curve, the agricultural water supply at each period throughout the year would be limited, i.e., the interactive effects from variables are noticeable at time periods from agr4-2 to agr5-3.

Additionally, comparisons are made among the optimized solutions from the final Pareto fronts, including the industry-favouring solution (S0), agriculture-favouring solution (S1), and compromised solution (S2). The comparisons of water shortage indices among different solutions are shown in Table 3, and the optimal rule curves for different solutions are shown in Fig. 8.

It could be seen from Table 3 and Fig. 8 that there are larger differences among different solutions. With the industry-favouring solution (S0), the agricultural water supply curve at the period from April to May is the highest among the three solutions. Because the agricultural water demand is very high during the non-flood period from April to May, the highest position of the agricultural water supply curve at these periods could be caused by the agricultural water demand not being satisfied at the first few periods of the agricultural water supply operation rule curve, and the agricultural water supply at each period throughout the year would be limited easily. Therefore, in S0, the industrial water demand could be fully satisfied through limiting agricultural water supply to a large extend, and lowering the industrial

Table 3. Comparisons of water shortage indices among different solutions.

Solutions	Water shortage index (–/no units)	
	Industrial water demand	Agricultural water demand
(S0) Industry-favouring solution	0.000	3.550
(S1) Agriculture-favouring solution	0.020	1.380
(S2) Compromised solution	0.007	1.932

water supply curve; industrial and agricultural water shortage indices are 0.000 and 3.550, respectively. Opposite to S0, the agricultural water demand in S1 could be satisfied largely through lowering the agricultural water supply curve on the period from April to May and raising the industrial water supply curve; and industrial and agricultural water shortage indices are 0.020 and 1.380, respectively. Compared with solutions S0 and S1, two objectives are balanced in the compromised solution (S2), where industrial and agricultural water shortage indices are 0.007 and 1.932, respectively.

5.2 Inter-basin multi-reservoir system

5.2.1 Sensitivity analysis

Similarly to the Dahuofang case study, a set of 2000 Latin hypercube samples were used per decision variable yielding a total number of $2000 \times (126+2) = 256\,000$ model simulations to compute Sobol's indices in this case study.

The first-order and total-order indices for 126 decision variables are shown in Fig. 9. Similarly to the results obtained from the Dahuofang ROS problem in Fig. 4, the variance in the two objectives, i.e., industrial and agricultural shortage indices, are largely controlled by the water storages at time periods from agr4-2 to agr5-3 of Shenwo reservoir water supply operation rule curves for agricultural water demand, and the water storages at time periods from agr4-2 to agr5-3 of Dahuofang reservoir water supply operation rule curves for agricultural water demand, the water storages at time periods ind1, ind2, ind3, ind7-1, ind10, ind11, and ind12 of Dahuofang reservoir water supply operation rule curves for industrial water demand based on a total-order Sobol's index threshold of greater than 3 %, which is subjective and its ease-of-satisfaction decreases with increasing numbers of parameters or parameter interactions. These 17 time periods are obvious candidates for reducing the dimension of the original optimization problem and formulating a pre-conditioning problem. Therefore, the simplified problem is defined from the original design problem with the 109 intensive time periods removed, while the insensitive decision variables are set randomly first with domain knowledge and kept constant during the solution of the simplified problem. The increased interactions across sensitive time periods in this test case

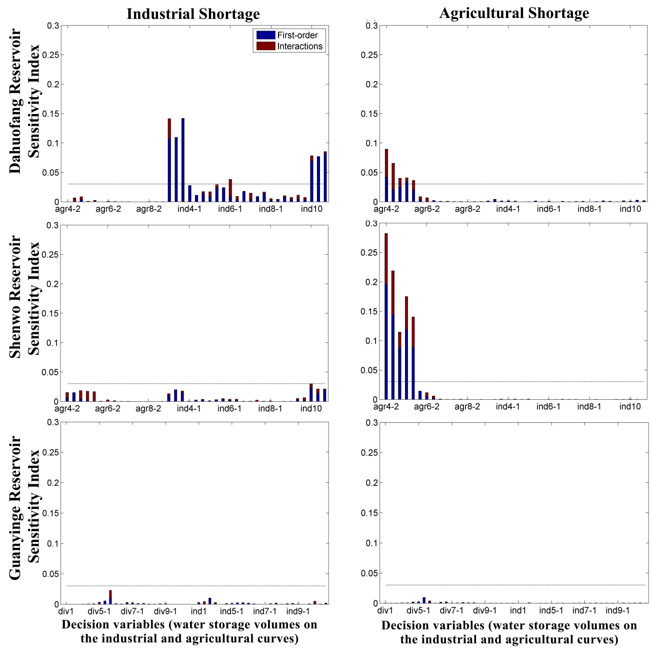

Figure 9. First-order and total-order indices for the inter-basin multi-reservoir operation problem regarding industrial shortage index and agricultural shortage index. The x axis labels represent decision variables (water storage volumes on the industrial, agricultural and water transferring curves).

should be noted; these interactions verify that this problem represents a far more challenging search problem.

5.2.2 Pre-conditioned optimization

Using the sensitivity-informed methodology, the simplified problem was first solved using ε-NSGAII with a maximum NFEs of 5000, and the Pareto-optimal solutions combined with the constant insensitive decision variables were then used as starting points to start a completely new search with a maximum NFEs of 495 000. The standard search using ε-NSGAII was set to a maximum NFEs of 500 000 so that the two methods have the same NFEs used for search. In this case, 10 random seed trials are used given the computing resources available. Similarly to the results obtained from the Dahuofang ROS problem in Fig. 5, the search traces in Fig. 10 show all three metrics (generational dis-

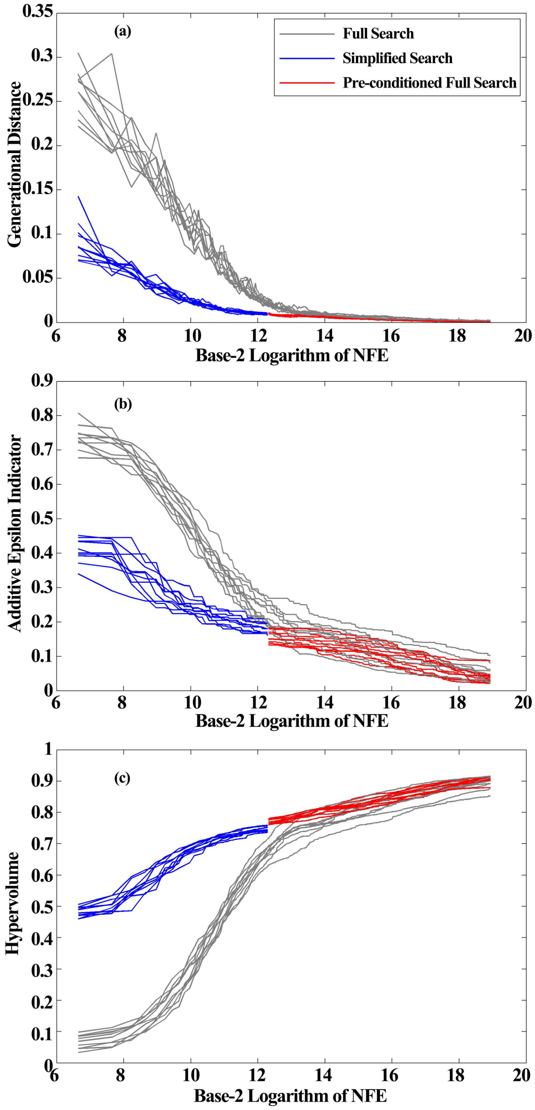

Figure 10. Performance metrics for the inter-basin multi-reservoir water supply operation problem – **(a)** generation distance, **(b)** additive epsilon indicator, and **(c)** hypervolume.

tance, additive epsilon indicator, and hypervolume) that represent performance metrics for the inter-basin multi-reservoir water supply operation system problem. Similarly, the pre-conditioning results are shown in Fig. 10 in red search traces continuing from the blue reduced complexity search results. It is clear that the sensitivity-informed pre-condition problems enhance search efficiency in terms of the generational distance, additive epsilon indicator, and hypervolume metrics. However, with the increase in problem complexity in comparison to the first case study (i.e., the number of decision variables from 39 to 126), the search of the ROS optimization problem becomes more difficult, and so the metrics obtained from the pre-conditioned search are not improved greatly compared with the standard baseline search. Both Figs. 5 and 10 show that sensitivity-informed dimension reduction and pre-conditioning could also yield strong efficiency gains and more reliable search (i.e., narrower band widths on search traces) for the inter-basin multi-reservoir system.

Figure 11a shows Pareto fronts from a NFEs of 6000, 8000 and 10 000 in the evolution process of one random seed trial. In the case of the pre-conditioned search, the solutions from the three NFE snapshots are much better than those from the standard baseline search. Similar to Fig. 6a, the results show that the Pareto-approximate front of the pre-conditioned search is much wider than that of the standard search, and clearly dominates that of the standard search in all the regions across the entire-objective space. Additionally, in the case of the pre-conditioned search, the solutions from 6000 evaluations are as good as those from 8000 evaluations and 10 000 evaluations. Furthermore, they are much better than the solutions from the standard baseline search. It should be noted that the slow progress in the Pareto-approximate fronts from 6000 to 10 000 evaluations reveals the difficulty of the inter-basin multi-reservoir operation system problem.

Figure 11b shows the best and worst Pareto fronts from a NFEs of 500 000 in the evolution process of 10 seed trials. Although it is obvious that the best Pareto-approximate front of the pre-conditioned is approximately as good as that of the standard search in all the regions across the entire-objective space, the Pareto solutions from 10 trials of the pre-conditioned search have significantly reduced variation, indicating a more reliable performance of the pre-conditioned method. In other words, the results show that the Pareto solution from one random seed trial of the pre-conditioned search is as good as the best solution from 10 random seed trials of the standard search. That is to say, in the case of the pre-conditioned search, one random seed trial with a NFEs of 500 000 is sufficient to obtain the best set of Pareto solutions; however, in the case of the standard search, 10 seed trials with a total of $500\,000 \times 10 = 5\,000\,000$ NFEs are required to obtain the Pareto solutions. Note that the NFEs of Sobol's analysis are 256 000, which is about half of the NFEs of one random seed trial. Thus, an improvement in search reliability can significantly reduce the computational demand for a complex search problem such as the multi-reservoir case study, even when the computation required by sensitivity analysis is included.

5.3 Discussions

The methodology tested in this study aims to reduce the number of decision variables through sensitivity-guided dimension reduction to form simplified problems. The optimization results from the two ROS problems show the reduction in decision space can make an impact on the reliability and efficiency of the search algorithm. For the Dahuofang ROS problem, recall that the original optimization problem has 39 decision variables, and the simplified problem has 11 de-

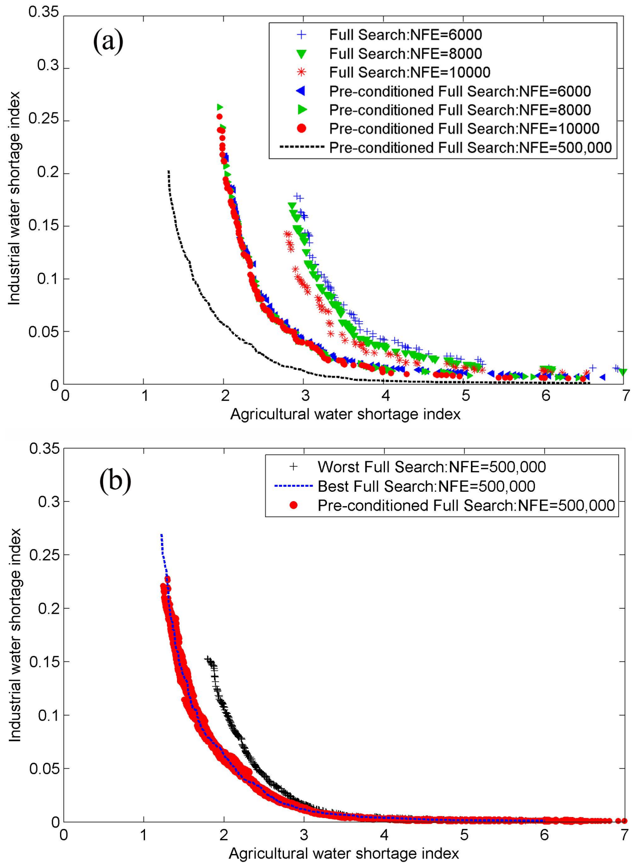

Figure 11. Pareto fronts derived from pre-conditioned and standard full searches for the inter-basin multi-reservoir operation problem. **(a)** Sample Pareto fronts with different numbers of function evaluations for one random seed trial. **(b)** The best and worst Pareto fronts of 10 seed trials.

cision variables based on Sobol's analysis. In the case of the inter-basin multi-reservoir operation system, the original optimization problem has 126 decision variables, and the simplified problem has a significantly reduced number of decision variables, i.e., 17. Searching in such significantly reduced space formed by sensitive decision variables makes it much easier to reach good solutions.

Although Sobol's global sensitivity analysis is computationally expensive, it captures the important sensitive information between a large number of variables for ROS models. This is critical for correctly screening insensitive decision variables and guiding the formulation of ROS optimization problems of reduced complexity (i.e., fewer decision variables). For example, in the Dahuofang ROS problem, accounting for the sensitive information, i.e., using total-order or first-order indices, results in a simplified problem for a threshold of 10 % as shown in Fig. 4. Compared with the standard search, this sensitivity-informed method dramatically reduces the computational demands required for attaining high-quality approximations of optimal ROS trade-offs relationships between conflicting objectives, i.e., the best Pareto fronts from a NFEs of 8000 in the case of the pre-condition search are approximately the same as the best Pareto front from a NFEs of 500 000 in the case of the standard baseline search.

In reality, for a very large and computationally intensive problem, the full search with all the decision variables would likely be so difficult that it may not be optimized sufficiently. However, as shown here, these simplified problems can be used to generate high-quality pre-conditioning solutions and thus dramatically improve the computational tractability of complex problems. The framework could be used for solving the complex optimization problems with a large number of decision variables.

For example, Fu et al. (2012) has used the framework for reducing the complexity of the multi-objective optimization problems in water distribution system (WDS), and applied it to two case studies with different levels of complexity – the New York tunnels rehabilitation problem and the Anytown water distribution network rehabilitation/redesign problem. For the New York tunnels network, because the original optimization problem has 21 decision variables (pipes) and each variable has 16 options, the decision space is $16^{21} = 1.934 \times 10^{25}$. The simplified problem with eight decision variables based on Sobol's analysis have a decision space of $16^8 = 4.295 \times 10^9$. To obtain the same threshold of hypervolume value 0.78 for the New York tunnels rehabilitation problem, the most pre-conditioned search need is 30 to 40 % of the NFEs compared to the full search through 50 random seed trials. In the case of the Anytown network, the original problem has a space of 2.859×10^{73}, and the simplified problem has a significantly reduced space of 8.364×10^{38}. Through 50 random seed trials for the Anytown rehabilitation/redesign problem, the full search requires an average of 800 000 evaluations to reach hypervolume value 0.77, and the pre-conditioned search exceeds the hypervolume value of 0.8 in all trials in fewer than 200 000 evaluations. The results also show that searching in such significantly reduced space formed by sensitive decision variables makes it much easier to reach good solutions, and the sensitivity-informed reduction of problem size and pre-conditioning improve the efficiency, reliability, and effectiveness of the multi-objective evolutionary optimization.

It should be noted that the framework for sensitivity-informed dimension reduction of optimization problems is completely independent of multi-objective optimization algorithms; that is, any multi-objective algorithms could be embedded in the framework. When dealing with three or more objectives, the formulation of the optimization problems with a significantly reduced number of decision variables will dramatically reduce the computational demands required to attain Pareto-approximate solutions in a similar way to the two-objective optimization case studies considered in this paper.

6 Conclusions

This study investigates the effectiveness of a sensitivity-informed optimization method for the ROS multi-objective optimization problems. The method uses a global sensitivity analysis method to screen out insensitive decision variables and thus forms simplified problems with a significantly reduced number of decision variables. The simplified problems dramatically reduce the computational demands required to attain Pareto-approximate solutions, which themselves can then be used to pre-condition and solve the original (i.e., full) optimization problem. This methodology has been tested on two case studies with different levels of complexity – the Dahuofang reservoir and the inter-basin multi-reservoir system in Liaoning province, China. The results obtained demonstrate the following:

1. The sensitivity-informed dimension reduction dramatically increases both the computational efficiency and effectiveness of the optimization process when compared to the conventional, full search approach. This is demonstrated in both case studies for both MOEA efficiency (i.e., the NFEs required to attain high-quality trade-offs) and effectiveness (i.e., the quality approximations of optimal ROS trade-offs relationships between conflicting design objectives).

2. The Sobol's method can be used to successfully identify important sensitive information between different decision variables in the ROS optimization problem and it is important to account for interactions between variables when formulating simplified problems.

Overall, this study illustrates the efficiency and effectiveness of the sensitivity-informed method and the use of global sensitivity analysis to inform dimension reduction. This method can be used for solving the complex multi-objective optimization problems with a large number of decision variables, such as optimal design of water distribution and urban drainage systems, distributed hydrological model calibration, multi-reservoir optimal operation and many other engineering optimization problems.

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