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Assessment of evolutionary algorithms for optimal operating rules design in real Water Resource Systems☆

Néstor Lerma [a,*], Javier Paredes-Arquiola [a], Joaquín Andreu [a], Abel Solera [a], Giovanni M. Sechi [b]

[a] Research Institute of Water and Environmental Engineering, (IIAMA), Universitat Politècnica de València, Camino de Vera S/N, 46022 Valencia, Spain
[b] Department of Civil, Environmental and Architectural Engineering (DICAAR), Università di Cagliari, Via Marengo 2, 09131 Cagliari, Italy

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A B S T R A C T

Two evolutionary algorithms (EAs) are assessed in this paper to design optimal operating rules (ORs) for Water Resource Systems (WRS). The assessment is established through a parameter analysis of both algorithms in a theoretical case, and the methodology described in this paper is applied to a complex, real case. These two applications allow us to analyse an algorithm's properties and performance by defining ORs, how an algorithm's termination/convergence criteria affect the results and the importance of decision-makers participating in the optimisation process. The former analysis reflects the need for correctly defining the important algorithm parameters to ensure an optimal result and how the greater number of termination conditions makes the algorithm an efficient tool for obtaining optimal ORs in less time. Finally, in the complex real case application, we discuss the participation value of decision-makers toward correctly defining the objectives and making decisions in the post-process.

1. Introduction

Over the last two decades, Evolutionary algorithms (EAs) have been applied extensively to a number of areas of water resources, such as water distribution systems (Goldberg and Kuo, 1987; Savic and Walters, 1997), urban drainage and sewage systems (Guo et al., 2008), water supply and sewage treatment systems (Murthy and Vengal, 2006), hydrologic and fluvial models (Muleta and Nicklow, 2005) and subterranean systems (Dougherty and Marryott, 1991), as highlighted in a review by Nicklow et al. (2009). However, while EAs have been applied successfully to many academic problems, additional research is required to enable them to be applied in real-life context (Maier et al., 2014). For example, there is a need to determine which searching mechanisms and termination/convergence criteria are best for real-life problems and the best way to convey the results of the optimisation process to decision makers (Maier et al., 2014). Consequently, these issues are the focus of this paper.

Simulation models are the most commonly used tool to analyse the integrated planning and management of WRS. These models allow for more detailed representations of the systems than do the optimisation models (Loucks and Sigvaldason, 1982). Moreover, the applicability of optimisation models to system management for most real reservoirs is limited due to the "high level of abstraction" needed for the efficient implementation of optimisation techniques (Akter and Simonovic, 2004; Moeni et al. 2010).

Normally, simulations of water management systems use operating rules (ORs) to model the efficient management of water resources. Designing and obtaining ORs for multi-reservoir systems is a complex task and has been widely developed during the scientific history of water resource studies (Young, 1967; Bhaskar and Withlach, 1980; Lund and Ferreira, 1996). On the other side, ORs must be implementable in real applications and therefore need to be robust as well as simple to be defined by a set of indicators and parameters.

A common technique used to design ORs is based upon iterative simulations of water management models. In this case, the goal is to find an OR that optimises system management. Therefore, the iterative process to find such an OR can be controlled by an optimisation algorithm that is responsible for varying the OR parameters based upon the results obtained from the simulation. EAs afford several benefits compared with classical optimisation

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* Corresponding author.
E-mail address: nestorlerma@upv.es (N. Lerma).

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techniques because they can be implemented without heavy a-priori model requirements, and thanks to their ability to manage discrete variables, EA optimisation procedures can directly address alternatives when applied to OR optimisation. To this end, EAs present effective an optimisation algorithm for searching for optimal rules in WRSs. For example, Oliviera and Loucks (1997), and later Ahmed and Sarma (2005), presented an approach for the optimisation of ORs in multi-reservoir systems using EAs. Other cases are reported by Cai et al. (2001) to solve nonlinear models of water management using a combination of an EA and linear programming; by Momtahen and Dariane (2007), who used a direct search approach to optimize the parameters of reservoir operating policies with a EA as an optimization method; or by Elferchichi et al. (2009), who applied an EA to optimise reservoir operations in the Sinistra Ofanto (Foggia, Italy) irrigation system. Furthermore, in the literature were used another metaheuristic approaches such as Guo et al. (2013), who incorporated a multi-population mechanism into a non-dominated sorting particle swarm optimization to obtain optimal rules for a water-supply reservoir; or as in Hossain and El-Shafie (2014) where a nonlinear reservoir release optimization problem was resolved by comparing evolutionary methods and swarm intelligences.

The main purpose of this paper is to test EAs and scattered search approaches to design ORs that optimise WRS management. The EAs used are the SCE-UA (Duan et al. 1992) and the Scatter Search (Glover, 1997), which are combined with the SIMGES network flow simulation model to design optimal ORs. In addition, an analysis of the parameters of both algorithms is carried out, which allows us to determine which termination/convergence criteria are most appropriate for realistic problems, apart from showing the most influential parameters that affect the optimisation process. On the other hand, the previous analysis and the use of one of these EAs in a real complex case demonstrate which of the two studied algorithms is the best for solving this type of problem. Finally, a method of transmitting the optimisation results is presented to make the decision-making easier. To analyse the parameters, a simple theoretical model representing a fictitious WRS is used. In the application for a real complex WRS, the Tirso-Flumendosa-Campidano system located on Sardinia Island (Italy) is used.

2. Materials and methods

We propose a connection between EAs (SCE-UA or Scatter Search) and a traditional water allocation model (SIMGES) in the water resources field to design optimal ORs for real WRSs. The approach developed is detailed in Fig. 1. Decision variables, OR parameters, are defined by the user and are sought by the EA to design optimal ORs for the WRS to which it is applied. Moreover, some algorithm-specific parameters, such as population size, the number of subgroups or the maximum number of iterations should be indicated to the EA, apart from the decision variables, to allow optimisation. Every EA implements the optimisation process as outlined below; the EA generates several individuals (or solutions) that belong to an OR collection. In our case, each OR aptitude depends on how it affects the WRS management. For this reason, WRS management is simulated through the SIMGES network flow for each OR, and the obtained results allow the EA to evaluate the objective function (OF). Given the value for each individual (or solution) of that OF, the algorithm obtains new values for the decision variables defining the OR, and the process is repeated until the stop condition for each EA is fulfilled.

Both algorithms have been repeatedly used in different areas of research. The SCE-UA algorithm is implemented in this study due to its demonstrated efficiency, which has been widely recognised in calibrating hydrological problems with a large number of parameters and with a high nonlinearity (Duan et al., 1992; Luce and Cundy, 1994; Kuczera, 1997; Boyle et al., 2000). On the contrary, the use of the Scatter Search application to design OR is currently uncommon but has been successfully applied in distribution network calibration problems (Liberatore and Sechi, 2009) as well as a wide range of more general optimisation problems (Martí, 2006; Campos et al., 2001; Scheuerer and Wendolsky, 2006; Adenso-Díaz et al., 2006). However, we have chosen the second algorithm because, unlike most conventional EAs such as the SCE-UA, thanks to the adoption of search and selection techniques, the population is much smaller than when using other EAs.

2.1. SCE-UA algorithm

The SCE-UA optimisation mechanism (the Shuffled Complex Evolution) was developed by Duan et al. (1992) at the University of Arizona. As mentioned above, its efficiency has been successfully tested to calibrate problems of hydrological models with a large number of parameters and with a high nonlinearity. The basic operation of the SCE-UA algorithm, inspired by the principles of natural selection and genetics, is a combination of deterministic and random processes. The departing point is from different search points (*individuals*) that are organised by teams (*complexes*). Searching for the globally optimised solution, an evolutionary process (evolution) is designed. This process is based on different reproduction methods such as crossing, mutation or recombination, and team mixing (shuffle). An extended SCE-UA technical details can be found in Duan et al. (1992).

2.2. Scatter Search algorithm

The Scatter Search algorithm (Glover, 1997) is a metaheuristic procedure based upon formulations of strategies for generating candidate solutions, and thanks to the adoption of search and selection techniques, the point population used is much smaller than is necessary for other techniques. The concepts and principles of this method are based on the strategy of combining decision rules. The Scatter Search operates on a set of solutions, called the Reference Set, and combines them to create new solutions that improve the original ones. In this sense, the Scatter Search should be considered as an EA. However, contrary to other evolutionary methods, such as genetic algorithms, the Scatter Search algorithm is not based upon randomness over a relatively large group of solutions but is based upon systematic and strategic choices over a small group. Typically, genetic algorithms consider large population sizes (100 solutions as an order of magnitude), whereas the Scatter Search utilises an equivalent set of only 10 solutions.

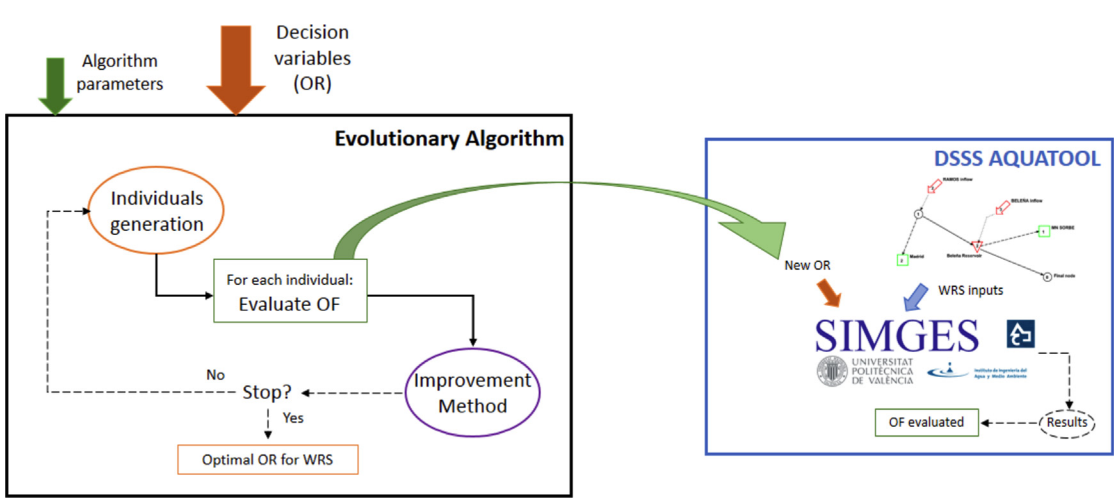

Fig. 1. Methodology. EA combined with the network flow SIMGES.