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Assessment of a parallel evolutionary optimization approach for efficient management of coastal aquifers

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A B S T R A C T

This study presents a parallel evolutionary optimization approach to determine optimal management strategies of large-scale coastal groundwater problems. The population loops of evolutionary algorithms (EA) are parallelized using shared memory parallelism to address the high computational demands of such applications. This methodology is applied to solve the management problems in an aquifer system in Kish Island, Iran using a three-dimensional density-dependent groundwater numerical model. EAs of continuous ant colony optimization (CACO), particle swarm optimization, and genetic algorithm are utilized to solve the optimization problems. By implementing the parallelization strategy, a speedup ratio of up to 3.53 on an 8-core processor is achieved in comparison with serial model. Based on solution quality and computational time criteria, the CACO robustness is observed in comparison to other EAs. Moreover, the optimization solution of the case study for a scenario of sea-level-rise indicates that a reduction of 20% in groundwater extraction rate is mainly due to the land-surface inundation caused by sea-level rise.

1. Introduction

Decision models are vital tools for optimal management of groundwater resources. Combined simulation-optimization framework has been widely employed for these models, where a process-based simulator is combined with an optimization algorithm. The optimization procedure is based on an iterative process that requires many simulation-based evaluations to optimize an objective function and to satisfy problem constraints. A challenging task in the application of such approaches at large-scale applications is the considerable computational time as large numbers of simulations are required (Werner et al., 2013; Ketabchi and Ataie-Ashtiani, 2015b). Hence, the reduction of total computational time and the number of simulations have a substantial impact on the final computational efficiency (Mirghani et al., 2009; Ketabchi and Ataie-Ashtiani, 2015a,b). Recently, Ketabchi and Ataie-Ashtiani (2015b) provided a complete and systematic review of the possible tools such as parallel processing techniques (e.g., Tang et al., 2010; Ketabchi and Ataie-Ashtiani, 2015b) and novel and efficient optimization algorithms (e.g., Ketabchi and Ataie-Ashtiani, 2015a,b; Yang et al., 2015) to address how the challenge of computational burden of decision models can be handled. They also summarized the remaining challenges for future research in this field and presented the practical solutions to solve a real-world coastal groundwater management problem. In the following, firstly, we briefly introduce the parallel processing techniques and their application in the groundwater resources field. Then, the approaches of an efficient EA choice are overviewed.

In the recent decades, with a rapid development of high performance computing technologies, parallel processing technique has been emerged from theories to applications. Parallel processing is the simultaneous use of more than one processor core to execute several computational threads (Parhami, 2002). This technique essentially implements distributed or shared memory parallelism (Parhami, 2002; Jin et al., 2011; Zhang et al., 2014). In the groundwater resources field, there are several successful examples of parallel processing application. Some key examples include fluid flow simulation in unsaturated zone of Yucca Mountain, Nevada (Zhang et al., 2003), biodegradation modelling in groundwater (Watson et al., 2005), groundwater inverse modelling (Sayeed and Mahinthakumar, 2005; He et al., 2007; Commer et al., 2014), optimal groundwater remediation design (He et al., 2007), long-term groundwater monitoring design (Tang et al., 2007),

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combined numerical pollutant-transport simulation and EA optimization (Mirghani et al., 2009), groundwater model calibration (Tang et al., 2010), integrated surface-subsurface water flow simulation (Hwang et al., 2014), groundwater flow simulation (Cheng et al., 2014), and surrogate-based coastal groundwater management in Kish Island, Iran (Ketabchi and Ataie-Ashtiani, 2015b).

Mirghani et al. (2009) adopted the application of a parallel simulation-optimization approach for pollution source identification in groundwater problems. In their approach, several hundreds to thousands of forward model evaluations were typically required during the EA search. The performance of their parallel simulation-optimization approach was demonstrated in terms of solution quality and computational performance. Cheng et al. (2014) suggested that in the groundwater simulation, parallel processing was an influential alternative approach to solve large-scale problems. Tang et al. (2010) highlighted the need to understand how such approaches were easily implemented to speed up groundwater model computations. Ketabchi and Ataie-Ashtiani (2015b) showed that the performance of a surrogate-based management model can be significantly enhanced by application of shared memory parallelization strategy.

In shared memory parallelism, communication between threads is achieved by sending to and receiving directly from shared memory. It is easy to solve the traditional programming problem of load balancing as it is automatically done using shared memory parallelism. Therefore, we need not consider which part of computation should be done on which core (Zhang et al., 2014). This approach can be accomplished on multi-core computers (Maris and Wannamaker, 2010). The attention to the application of shared memory parallelism approaches has significantly increased with the development of multi-core computers (McLaughlin, 2008; Tang et al., 2010). Shared memory parallelism provides the advantages of simplicity, good extendibility, and portability via an efficient and easy-to-use framework (Amritkar et al., 2012; Zhang et al., 2014; Ketabchi and Ataie-Ashtiani, 2015b).

The choice of efficient optimization algorithms is another strategy to address high computational demands. Surveying the recent literature demonstrates an increasing trend towards the application of evolutionary algorithms (EAs) to solve groundwater management problems (Singh, 2015; Maier et al., 2014; Ketabchi and Ataie-Ashtiani, 2015a,b; Zheng et al., 2015). Considering the large number of EAs and their variants, the efficient choice of EAs for the purposes of groundwater managements is still an open challenge. Ketabchi and Ataie-Ashtiani (2015a) presented the comparative assessments on the efficiency and robustness of eight EAs [genetic algorithm (GA), continuous ant colony optimization (CACO), particle swarm optimization (PSO), differential evolution, harmony search, shuffled complex evolution, artificial bee colony, and simplex simulated annealing] to solve the four benchmark coastal groundwater management problems. They recommended the application of CACO and PSO in this field in terms of both solution quality and computational time criteria. Then, Ketabchi and Ataie-Ashtiani (2015b) extended the comparisons to a surrogate-based real-world management problem solved by use of six EAs (GA, CACO, PSO, differential evolution, harmony search, and shuffled complex evolution) and focused on the criterion of computational time. In their study, the superiority of CACO and PSO relative to other EAs was also shown.

1.1. Study objectives

This study is a significant step forward of Ketabchi and Ataie-Ashtiani (2015b) work on the application of parallel evolutionary-based optimization models for the solving of coastal groundwater management problems and aims to thoroughly describe the aspects of such advance for a variety of real-world management problems. Also, comparing the efficiency of EAs in this field for the real-case application is a novel task in advancing the recent investigations of Ketabchi and Ataie-Ashtiani (2015a) on hypothetical benchmark cases and Ketabchi and Ataie-Ashtiani (2015b) on a surrogate-based real-world case. In this study, we evaluate the application of both CACO and PSO algorithms as the optimization tools based on Ketabchi and Ataie-Ashtiani (2015a,b). Also, GA as the most popular of EAs (Singh, 2014, 2015; Ketabchi and Ataie-Ashtiani, 2015b) is also evaluated.

Here, we address: (1) how the shared memory parallelism can be utilized to solve a real-world problem which involves thousands of time-consuming forward runs (i.e. large required computational time) and to what extent this approach is successful; and (2) how EAs of CACO, PSO, and GA are practically implemented to solve real-world management problems and among them which one is the most effective and robust. To cover these objectives, we have formulated the management problems of Kish Island aquifer system, located in the Persian Gulf, Iran, for obtaining appropriate optimal extraction strategies (Ataie-Ashtiani et al., 2014). Several factors like the determination of optimal extractions from management zones, the controlling of seawater intrusion (SWI), and the assessment of climate change impacts (e.g., the influences of sea-level rise, land-surface inundation caused by it, and variations in recharge rates) are considered in this assessment.

2. Materials and tools

A combined simulation-optimization framework is considered as presented in the schematic flowchart of Fig. 1. A similar framework has been employed by Abd-Elhamid and Javadi (2011), Ataie-Ashtiani and Ketabchi (2011), Sreekanth and Datta (2014), Ataie-Ashtiani et al. (2014), and Ketabchi and Ataie-Ashtiani (2015a,b). As seen in Fig. 1, the main features of this study are the application of a transient three-dimensional numerical model, an optimization tool based on EAs, and parallelization. The optimization tool calls the simulation model to verify the constraints and evaluates the objective function values and then updates decision variables. This procedure is repeated until the stopping criteria are met. Main components of this framework are described in the following sections.

2.1. Simulation approach

SUTRA simulator, three-dimensional saturated-unsaturated density-dependent flow and solute transport model (Voss and Provost, 2010), is used for numerical simulations. This model employs a finite element approximation of the governing equations in space and an implicit finite difference approximation in time. The governing fluid mass balance equation representing groundwater flow and the solute mass balance equation characterizing the solute transport in porous media are solved simultaneously to describe density-dependent flow associated with SWI (Voss and Provost, 2010). In addition, the automated parameter estimation code PEST (Doherty, 2005) is used for automatic calibration of the numerical model parameters. The procedures of numerical simulation and associated calibration are provided in Appendix A, based on Ataie-Ashtiani et al. (2014) and Mahmoodzadeh et al. (2014).

2.2. Optimization approach

EAs are robust to solve coastal groundwater management problems in spite of the non-linearity and complexity of these optimization problems (Nicklow et al., 2010; Singh, 2014). EAs work on a set of potential solutions, which is called, population, and find the optimal solution through search techniques after a sufficient