Ecological Indicators 48 (2014) 498–504

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Managing the environmental problem of seawater intrusion in coastal aquifers through simulation–optimization modeling

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ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form 2 September 2014
Accepted 8 September 2014

Keywords:
Seawater intrusion
Environmental problem
Simulation–optimization modeling
Response matrix approach
Embedding technique
Coastal aquifers

ABSTRACT

The seawater intrusion is a widespread environmental problem of coastal aquifers where more than two third of the world's population lives. The indiscriminate and unplanned groundwater withdrawal for fulfilling the growing freshwater needs of coastal regions causes this problem. Computer-based models are useful tools for achieving the optimal solution of seawater intrusion management problems. Various simulation and optimization modeling approaches have been used to solve the problems. Optimization approaches have been shown to be of great importance when combined with simulation models. A review on the combined applications of simulation and optimization modeling for the seawater intrusion management of the coastal aquifers are done and is presented in this paper. The reviews revealed that the simulation–optimization modeling approach is very suitable for achieving an optimal solution of seawater intrusion management problems even with a large number of variables. It is recommended that the future research should be directed toward improving the long-term hydraulic assessment by collecting and analyzing widespread spatial data, which can be done by increasing the observation and monitoring networks. The coupling of socioeconomic aspects in the seawater intrusion modeling would be another aspect which could be included in the future studies.

1. Introduction

The coastal aquifers of the world are facing the serious environmental problem of seawater intrusion (El-Bihery and Lachmar, 1994; Yakirevich et al., 1998; Pulido-Bosch et al., 1999; Don et al., 2006; Trabelsi et al., 2007; Sherif et al., 2012). This problem is mainly the result of indiscriminate and unplanned groundwater exploitation for fulfilling the growing freshwater needs of coastal regions as more than two third of the world's population lives in these areas (Singh, 2014a). Seawater intrusion is one of the major causes of groundwater quality degradation because mixing even a small quantity of 2–3% saltwater makes the groundwater unsuitable (Abd-Elhamid and Javadi, 2011) for domestic, agricultural, and industrial uses. The sea level rise, which is a result of global warming, also causes the seawater intrusion (Bobba, 2002; White et al., 2005; Bindoff et al., 2007; Masterson and Garabedian, 2007; Hunter, 2009; Sanford and Pope, 2010; Loaiciga et al., 2012). The rate of global mean sea level rise was 1.8 mm/year during the 20th century (Douglas, 1997). However, the rate of rise has been increasing during the last few decades and it is estimated at 3.3 mm/year for the period 1992–2010 (Nicholls and Cazenave, 2010). The first problem of seawater intrusion was reported in literature about two centuries ago (DuCommun, 1828). Since then numerous researchers around the world have carried out seawater intrusion studies (e.g., Brainthwaite, 1855; Charnes and Cooper, 1959; Gimenez and Morell, 1997; Iribar et al., 1997; Pulido-Laboeuf, 2004; Post, 2005; Psychoyou et al., 2007; Barlow and Reichard, 2010; Kalangutkar et al., 2011; Khomine et al., 2011; Ghiglieri et al., 2012; Masciopinto, 2013; Tornero and d'Alcala, 2014).

During the recent past, a large number of mathematical models have been used for solving the problems of seawater intrusion (Maimone, 2002; Cheng and Ouazar, 2004; Mantoglou and Papantoniou, 2008; Skiborowski et al., 2012). Different objective functions and sets of constraints have been employed depending on the problem, i.e., maximization of the total pumping rate (Shamir et al., 1984; Cheng et al., 2000; Abarca et al., 2006; Singh, 2012), minimization of saltwater volume into the aquifer (Hallaji and Yazicigil, 1996), minimization of drawdown (Finney et al., 1992; Emch and Yeh 1998), minimization of pumped water salinity (Das and Datta, 1999a,b), pumping cost (Reichard and Johnson, 2005; Ferreia da Silva and Haie, 2007), and multiple objectives (Das and Datta, 1999a; Park and Aral, 2004) etc.

A linear programming (LP) model was used by Molz and Bell (1977) for the design of a well field with the objective of maximizing total pumping by satisfying finite difference discretized flow

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http://dx.doi.org/10.1016/j.ecolind.2014.09.011
1470-160X/

equations of steady state conditions and specified head gradients. Willis (1983) used an LP model for the determination of the optimal pumping scheme. The objectives were to maximize the sum of hydraulic heads and minimize the total deficit of unconfined aquifer in the Yun Lin basin in Taiwan. Later, Willis and Finney (1988) utilized a planning and management model for the control of seawater intrusion in the same region of Taiwan. They considered the aquifer as unconfined. Karterakis et al. (2007) used a classical LP and heuristic optimization models for studying the groundwater management problem in coastal Crete aquifer, Greece. They performed a sensitivity analysis to examine the effect of active pumping wells on the evolution of the seawater intrusion front along the coastline.

The seawater intrusion is a very complex process (Bear et al., 1999) and requires nonlinear programming (NLP) techniques for handling the system nonlinearities (Gorelick et al., 1979). A quasi three-dimensional optimal control model was developed and applied for groundwater management in the Jakarta coastal aquifer basin (Finney et al., 1992). Sherif and Singh (1999), Ebraheem et al. (2003) and Gossel et al. (2004) have used numerical groundwater flow and solute transport models for estimating the hydraulic parameters and predicting the aquifer responses to different pumping scenarios and climate conditions. They concluded that these models can also simulate the fluctuations of the seawater–freshwater interface and transition zone due to salt dissolution, groundwater pumping, and evaporation (Sherif and Kacimov, 2005; Kacimov et al., 2009).

Ritzel et al. (1994) solved a multiobjective groundwater contamination problem using genetic algorithms (GA). Maximizing the reliability and minimizing the cost of the hydraulic containment were the two objectives of the model. A management model was developed by Mantoglou and Papantoniou (2008) for optimal design of pumping networks in coastal aquifers. The model was based on GA and numerical solution of the governing differential equations of freshwater flow. Haiso and Chang (2002), Espinoza et al. (2005), Horng et al. (2005), and Espinoza and Minsker (2006) have also utilized GA-based management models for the solution of groundwater management and pollution related problems. Shammas and Thunvik (2009) utilized a three-dimensional numerical model for the management of groundwater flow and solute transport in Salalah aquifer. They considered different scenarios for identifying the best scenario for groundwater levels and groundwater salinity for the year 2020.

The LP technique was extensively used for the management of seawater intrusion because of its easy formulation and application (Ahlfeld and Heidari, 1994), however this approach is limited to the problems where both, the objective function and constraints are linear. But the salt intrusion in coastal aquifers is a highly nonlinear process which requires an NLP approach for its appropriate solution (Gorelick et al., 1979; Casola et al., 1986). The nonlinearities in the aquifer management problems may arise due to nonlinear physical and managerial objective functions and constraints. The inability of conventional LP and NLP models in handling nonlinear non-convex problems and difficulty in attaining global optima generate demand for other types of algorithms. The GA (Holland 1975; Fogel 1994) has been established as a valuable tool for solving complex optimization problems during the recent past (Wu et al., 2007; Liu et al., 2008; Nicklow et al., 2010). The GA can yield much better results as compared to the traditional optimization techniques (Huang and Mayer, 1997). The main advantage of GA is that it does not require differentiability of objective function or/and constraint and it can handle large number of constraints as compared to the classical optimization techniques. This approach is particularly suitable for externally linking the numerical simulation model within the optimization model.

The seawater intrusion management problems of the coastal aquifers have been solved by using a large number of simulation and optimization models as mentioned above. However, during the recent years researchers have actively sought to combine simulation models with optimization techniques to address the problems. The simulation–optimization models have been extensively used by researchers around the world (e.g., Gorelick 1983; Ahlfeld et al., 1986; Katsifarakis and Petala, 2006; Ayvaz and Karahan, 2008; Kourakos and Mantoglou, 2009) for the management of seawater intrusion. As far as author is aware, there has not been a review on the combined applications of simulation–optimization modeling for the management of seawater intrusion, during the recent past. This paper, therefore, presents an overview of the combined applications of simulation–optimization modeling for the management of seawater intrusion in the coastal aquifers.

The paper is divided into five sections followed by list of references. Section 1 deals with the significance and rationale of the study along with its objectives. The development and application of simulation–optimization models for seawater intrusion management are provided in Section 2. The techniques of integrating the simulation and optimization models are provided in Section 3. Section 4 deals with the case studies pertaining to the use of simulation–optimization models for the management of seawater intrusion problems. Conclusions of the study are provided in Section 5.

2. Background

Generally, simulation models are used to examine a limited number of options by trial and error and provide the answer of 'what if'. Similarly, the optimization models answer the question of 'what is the best' under a particular set of conditions. However, it is unlikely to get an appropriate solution with simulation or optimization techniques alone, and thus the combined use of simulation and optimization models is essential (Seppelt et al., 2013; Singh and Panda, 2013; Singh 2014b,c). The first example of combined application of simulation–optimization (SO) models was reported in the literature during the early 1970s (Maddock, 1972). The SO models provide a useful framework for managing the groundwater resources (Ahlfeld and Mulligan, 2001). In the SO modeling framework, the simulation models are used to check the constraints of the problem which are based on state variables, i.e., groundwater level. The objective function is evaluated using the optimization model, which in turn, utilizes the simulation model to satisfy the constraints. The SO approach has shown its potential with the large number of state variables and a small number of control variables (Qahman et al., 2005). During the last few decades, the SO modeling approach have been widely used to solve the problems of groundwater resources in coastal regions (e.g., Wagner and Gorelick, 1989; Wang and Zheng, 1998; Mantoglou, 2003; Zhou et al., 2003). Willis and Yeh (1987), Yeh (1992), and Wagner (1995) have provided comprehensive reviews of the SO approach.

The SO approach is attractive because it can account for the complex groundwater flow behavior and identify the best management strategy for a given set of conditions. The SO models can also help to analyze impact vulnerability and adaptation to climate change scenarios considering all together groundwater and surface water resources and the interaction between them (Marino, 2001). Within the SO approach, the simulation models account for the physical behavior of groundwater systems, whereas optimization models account for the optimal allocation aspects. The simulation model MODFLOW (McDonald and Harbaugh, 1988) was coupled with the linear and mixed integer programming optimization model MODMAN by Jonoski et al.