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Optimal combined operation of production and barrier wells for the control of saltwater intrusion in coastal groundwater well fields

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ABSTRACT

This study develops a methodology based on simulation-optimization to derive optimal combined operation plans for the management of production and barrier wells in a coastal aquifer in order to ensure the sustainable use of the fresh water resource. A numerical model for the simulation of saltwater intrusion process, a neural network based meta-model and a multi-objective genetic algorithm are used in a linked simulation-optimization approach to develop the management model. The pumping strategies derived using the management model was found to be effective in finding optimal and sustainable operation strategies for coastal well fields by controlling saltwater intrusion.

Keywords: Optimization; Groundwater; Coastal aquifer

1. Introduction

Coastal aquifers are a major source of fresh groundwater in many parts of the world. It has been estimated that more than 60% of the ever increasing human population is concentrated within 60 km from the coasts [1]. Majority of the big cities of the world are located in the coastal zones as they are the zones of major socio-economic activities. The ever increasing settlements and growth of industry and associated activities puts stress on the available freshwater sources in the coastal zone. As the groundwater in coastal aquifers is hydraulically connected to the sea unplanned overexploitation of these groundwater resources leads to eventual contamination of the freshwater aquifer due to saltwater intrusion. Hence, careful planning is needed in the management of groundwater extraction from coastal aquifers. This study develops a methodology for the integrated management of pumping from production wells and barrier wells in a coastal aquifer.

Saltwater intrusion is defined as the inflow of saline water in an aquifer system. Salinity intrusion occurs due to the movement of seawater towards the freshwater aquifer thereby creating brackish environment. Near coastal areas, fresh water and seawater maintains equilibrium with the heavier seawater underlying the freshwater due to the hydrodynamic mechanism. A diffuse interface exists between them with the density of water gradually decreasing from the seawater side to the fresh water side. The mixing zone or transition zone has varying thicknesses depending on the coastal aquifer environment. Large scale saltwater intrusion problems occur when the interface between fresh and saline groundwater moves slowly and smoothly in upward and/or inland direction.

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This large scale displacement can be caused by groundwater abstraction, sea level changes, land reclamation and excavation etc.

Salinity intrusion in coastal aquifers is a highly non-linear and complex process [2]. Once salinity intrusion occurs, it involves long-term measures incurring huge costs to remediate these contaminated aquifers. Different structural and hydraulic measures are available to prevent saltwater intrusion [3]. Also water can be pumped out and treated using different water treatment methodologies to improve the water quality. However, these methods involve huge costs and are difficult to be applied for regional scale management of saltwater intrusion. The thrust of this study is to explore the possibility of managing the withdrawal strategies in space and time so as to maximize the groundwater extraction and simultaneously prevent the saltwater intrusion.

Numerical modeling based studies are used to understand the aquifer responses to groundwater extraction. These models are used to simulate the flow and transport processes occurring in the aquifer. Usually, in the groundwater simulation modeling the flow equations are solved first and the velocity of flow obtained from that is used in the transport equations to solve for the pollutant concentration. In the saltwater intrusion process the pollutant is the salinity from the seawater. This causes the density of the freshwater to increase as the mixing occurs. Due to the density dependence of the flow and transport equations and the salinity it is required to solve the flow and transport equations simultaneously. This induces high non-linearity and complexity in the modeling of saltwater intrusion process. Different numerical models have been used in the past for saltwater intrusion modeling. This includes both analytical and numerical models. Analytical models are based on Ghyben Herzberg approach which assumes that a sharp interface exists between the mixing fresh and saltwater. Although it is an approximate method analytical solutions can be obtained for the saltwater intrusion problem based on this approach. A number of studies have used the analytical approach to solve the saltwater intrusion problem [4–11]. All the analytical approaches approximate the saltwater intrusion problem by assuming a sharp interface to exist between the mixing saline and freshwater. A number of numerical models have been developed to solve the density dependent saltwater intrusion problem, a review of which can be found in Sorek and Pinder [12] and Dhar and Datta [13]. Most commonly used codes are SUTRA [14,15] FEMWATER [16], SEAWAT [17], HST3D [18], FEFLOW [19] etc. Management models for sustainable utilization of groundwater can be developed by using the numerical simulation models within an optimization algorithm. Linked simulation optimization has been used to solve different coastal aquifer management problems like pumping optimization, panning models for coastal aquifers, multi-objective optimization of pumping rates, conjunctive use of surface and groundwater etc. [20–28]. Cheng et al. [20] used genetic algorithm to optimize the pumping pattern of coastal aquifers. Mantoglou [21] used analytical solution of the saltwater intrusion equations within the optimization model to solve the pumping optimization problem. Park and Aral [22] solved a multi-objective optimization problem of coastal aquifer pumping management. A few case studies on saltwater intrusion management using linked simulation-optimization have been reported [23–28]. Das and Datta [29] developed a coastal aquifer management model which the numerical equations for the simulation of saltwater intrusion were embedded as constraints within a non-linear optimization model. Since the use of 3D numerical simulation models inside optimization algorithm involves huge computational burden, meta models are often used to replace the actual numerical models. The embedding technique and direct linking of the numerical models to the optimization models involve huge computational burden. A few studies have used properly trained and tested neural networks as meta-models for groundwater management [30–34]. Meta-models can reduce the computational burden of the management model. In this study neural network is used to surrogate the actual numerical simulation model to predict the aquifer responses in terms of salinity levels at the monitoring locations. Also the present work considers the management policy considering the combined operation of production and barrier wells together using a multi-objective optimization model.

In this study we develop a linked simulation-optimization model for coastal aquifer management model. The developed model is able to determine the optimal extraction strategies for operating the production bores and the barrier wells simultaneously. A 3D density dependent flow and transport simulation model FEMWATER is used to simulate the aquifer processes. A neural network based meta model trained and tested using the aquifer simulation data obtained from FEMWATWER is used to replace the simulation model within optimization. The coastal aquifer management problem is formulated as a multi-objective optimization problem and is solved using a multi-objective genetic algorithm.

2. Problem development

The methodology of linked simulation-optimization for simultaneous determination of the pumping strategies for production wells and barrier wells is illustrated for a small coastal well field. The aquifer is 2.52 km^2 in area and is bounded by the sea on the western side. The other boundaries of the aquifer are all no flow boundaries. The average aquifer thickness is 60 m. The seaside boundary has a constant head of 0 m and a constant concentration of 35 kg/m^3. The groundwater recharge into the aquifer is considered uniform throughout the top land surface at a rate of 20 cm/y. Eight production bores for pumping

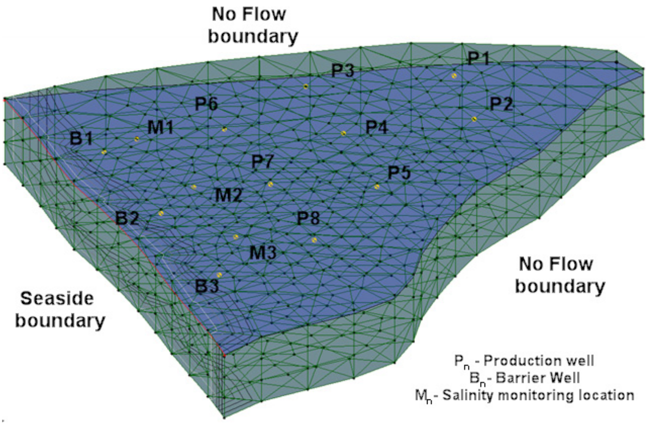

Fig. 1. Three dimensional view of the well field discritized into finite elements.

out fresh water from the aquifer are considered. The water quality is monitored at three monitoring locations. Also, three barrier wells tapping water from the saltwater wedge region is considered. The aquifer system is illustrated in Fig. 1. The production bore locations are indicated as P1, P2 etc and the barrier well locations as B1 B2 and B3. The salinity levels are monitored at three monitoring locations M1 M2 and M3. A management time horizon of 3 years is considered.

The pumping out of water from the production bores causes the inward movement of the saltwater wedge into the freshwater side by advection and dispersion. Hence, unsustainable rates of pumping from the production bores cause eventually contamination of the aquifer by saltwater intrusion. The barrier wells act as a measure of hydraulic control of saltwater intrusion. Pumping out of water from the barrier wells causes decrease in head near the saltwater wedge there by causing flow of water towards the sea from the aquifer, thus preventing saltwater intrusion. The pumping from the production bores and the barrier wells have opposite effects on the water quality of the aquifer. Larger volumes of groundwater extraction from the production bores require increased pumping from the barrier wells to maintain the water quality. However, the water pumped from the barrier wells will be highly saline and are not good for any practical use unless treatment measures are adopted. Hence, maximizing the total pumping from the production bores and simultaneously minimizing the total pumping from the barrier wells is the objective of management considered in this work.

The simulation model used in this study is FEMWATER [15]. FEMWATER is a three dimensional finite element based coupled flow and transport simulation model. The flow and transport equations used by the numerical model are given below.

3. Flow equations

$$\frac{\rho}{\rho_o} F \frac{\partial h}{\partial t} = \nabla . \left[\mathbf{K} . \left(\nabla h + \frac{\rho}{\rho_o} \nabla z \right) \right] + \frac{\rho^*}{\rho_o} q \tag{1}$$

$$F = \alpha' \frac{\theta}{n} + \beta' \theta + n \frac{dS}{dh} \tag{2}$$

$$\mathbf{K} = \frac{\rho g}{\mu} \mathbf{k} = \frac{\left(\rho / \rho_o \right)}{\left(\mu / \mu_o \right)} \frac{\rho_o g}{\mu_o} \mathbf{k_s} k_r = \frac{\rho / \rho_o}{\mu / \mu_o} \mathbf{K_{so}} k_r \tag{3}$$

$$\frac{\rho}{\rho_o} = a_1 + a_2 C \tag{4}$$

4. Transport equations

$$\theta \frac{\partial C}{\partial t} + \rho_b \frac{\partial S^a}{\partial t} + \mathbf{V} \cdot \nabla C - \nabla \cdot \left(\theta \mathbf{D} \cdot \nabla C \right) =$$
$$- \left(\alpha' \frac{\partial h}{\partial t} + \lambda \right) \left(\theta C + \rho_b S^a \right) - \left(\theta K_w C + \rho_b K_s S^a \right) + \tag{5}$$
$$m - \frac{\rho^*}{\rho} q C + \left(F \frac{\partial h}{\partial t} + \frac{\rho_o}{\rho} \mathbf{V} \cdot \nabla \left(\frac{\rho}{\rho_o} \right) - \frac{\partial \theta}{\partial t} \right) C$$

$$\mathbf{D} = a_T \,|\, \mathbf{V} \,|\, \delta + \left(a_L - a_T \right) \frac{\mathbf{VV}}{|\mathbf{V}|} + a_m \theta \tau \tag{6}$$

F = storage coefficient; h = pressure head; t = time; $\mathbf{K}$ = hydraulic conductivity tensor; z = potential head; q = source and/or sink; ρ = water density at the chemical concentration C; ρ_0 = referenced water density at zero chemical concentration; ρ^* = density of either the injection fluid or the withdrawn water; θ = moisture content; α' = modified compressibility of water; n = porosity of the medium; S = saturation; μ = dynamic viscosity of water at chemical concentration C; μ_o = referenced dynamic viscosity of water at zero chemical concentration; $\mathbf{k}$ = permeability tensor; $\mathbf{k_s}$ = relative permeability or relative hydraulic conductivity; $\mathbf{K_{so}}$ = referenced saturated hydraulic conductivity tensor; a_1, a_2 = parameters defining the concentration dependence; ρ_b = bulk density of medium; C = material concentration in aqueous phase; S^a = material concentration in adsorbed phase; V = discharge; ∇ = del operator; $\mathbf{D}$ = dispersion coefficient tensor; α' = compressibility of the medium; h = pressure head; λ = decay constant; $m = qC_{in}$ = artificial mass rate; q = source rate of water; C_{in} = material concentration in the source; K_w = first order biodegradation rate constant through dissolved phase; K_s = first order biodegradation rate through adsorbed phase.

The aquifer is discretized into triangular finite elements of side 150 m. A finer element size of 60 m is used near pumping wells. The model is set up and the aquifer response corresponding to different pumping patterns from the production wells and the barrier wells in terms of the resulting salinity levels at the monitored locations is evaluated using the model. The aquifer response to specific pumping patterns are then used to develop the ANN based meta model for use in optimization.

5. Neural network model

A neural network model trained using back-propagation algorithm is used to predict the aquifer responses corresponding to specific pumping patterns. The inputs to the neural network model are the rates of pumping from different production bores and the barrier wells and the outputs are the resulting salinity levels at the monitoring locations at the end of the management time horizon. The developed neural network model has 33 input nodes and 3 output nodes. A network architecture with one hidden layer was sufficient to predict the salinity levels satisfactorily. The number of nodes in the hidden layer was determined using trial and error approach. The neural network model is trained and tested using the input-output patterns of pumping and resulting salinity levels. Once trained and tested, the neural network model can substitute the actual numerical simulation model during optimization. Altogether 230 patterns of input-output were used to train the neural network model. The learning rate and momentum factor used was 0.1. Optimum number of hidden nodes was found to be 33 equal to the number of inputs to the model.

6. Management model

The management model uses the simulation model to evaluate different candidate solutions to the problem in a systematic manner to evolve the optimal solutions. For this an optimization algorithm is used. In the present study we use a multi-objective genetic algorithm called NSGA-II to solve the optimization problem [35].

This is because two conflicting objectives of optimization are considered. The primary objective is to maximize the total pumping from the production bores. The second objective is to minimize the total pumping from the barrier wells. Increased pumping from the production bores requires more pumping from the barrier wells to control the resulting saltwater intrusion hydraulically. Hence, these two objectives are conflicting objectives and multi-objective optimization is required to solve such problems. Multi-objective optimization problems have a set of non-dominated solutions which give a trade-off between the conflicting objectives rather than a single solution. The non-dominated set of solutions is called Pareto-optimal solution.

The mathematical formulation of the optimization model is as follows:

$$\text{Maximize } f_1(Q) = \sum_{\forall n} \sum_{\forall t} Q_n^t \tag{7}$$

$$\text{Minimize } f_2(Q) = \sum_{\forall m} \sum_{\forall t} q_m^t \tag{8}$$

$$\text{s.t. } c_i = \xi(Q, q) \tag{9}$$

$$c_i \le c_{\max} \forall i \tag{10}$$

$$Q_{\min} \le Q_n^t \le Q_{\max} \tag{11}$$

$$q_{\min} \le q_m^t \le q_{\max} \tag{12}$$

where Q_n^t is the pumping from the n^{th} production well during t^{th} time period, q_m^t is the pumping from the m^{th} barrier well during t^{th} time period and c_i is the concentration in the i^{th} monitoring well at the end of the management time horizon. ξ ( ) represents the density dependent flow and transport simulation surrogate model and constraint (9) represents the coupling of the surrogate model with the optimization model Constraint (10) imposes the maximum permissible salt concentration in the monitoring well locations. Constraints (11) and (12) define lower and upper bounds of the pumping from production wells and barrier wells respectively.

The upper and lower bounds for the pumping rates were specified with practical limits of 1300 m^3/d and 0 m^3/d, respectively. Altogether the optimization problem has 33 variables corresponding to pumping from 11 locations for three time periods. Out of this 3 locations correspond to barrier well locations.

The optimization algorithm starts with randomly generated candidate solutions for the coastal well field management problem. These candidate solutions are pumping patterns for the production wells and barrier wells. These solutions are then sent to the neural network model which evaluates the aquifer responses in terms of the salinity levels at the monitoring locations. The optimization model specifies that these resulting salinity levels should be within acceptable limits. Thus different candidate solutions are evaluated for the maximum total pumping from the production wells and minimum from the barrier wells which satisfies the imposed constraints of salinity limits.

Multi-objective genetic algorithm uses a population based optimization search [35]. The population of randomly generated candidate solutions are evaluated for their objective function value. Then they are selected and operated upon by genetic algorithm operators called cross-over and mutation to create new population of solutions. This procedure is repeated for a number of generations upon which the solutions are improved and converge to the optimal solution.

7. Results and discussion

A management model was developed for a small coastal well field with 8 production wells and 3 barrier wells. A finite element based simulation model was set up for the study area with proper initial and boundary conditions. The simulation model was used to determine the aquifer responses to different pumping patterns and these patterns of pumping values and corresponding aquifer responses were used to train and test a neural network model. The trained and tested neural network model was linked to the multi-objective optimization algorithm to derive the optimal pumping strategies for the well field.

The multi-objective optimization algorithm used a population size of 200 and 750 generations to derive the optimal solutions. The optimum crossover and mutation parameters used were respectively 0.9 and 0.05. The Pareto-optimal set of solutions obtained for this pumping optimization problem is shown in Fig. 2. Each solution on the front corresponds to a combination of pumping from the production bores and the barrier wells. Therefore, optimal pumping from the production bores in order to maximize the total pumping is given by this solution. Simultaneously, the corresponding optimal pumping from the barrier wells required to maintain the water quality is also obtained from the same solution.

The Pareto-optimal front shows a trade-off between the two objectives of well field management. On the front, any increase in the total pumping from the production bores require an increase in the barrier well pumping also. Practically increase in the production bore pumping causes the saltwater wedge to move towards land. This needs to be compensated by increased barrier well pumping which causes groundwater flow gradient towards the sea there by compensating the effect caused by the production bore pumping. The pumping rates from the production wells and barrier wells corresponding to three different solutions of the Pareto-optimal front are given in Figs. 3–5. In the figures, the X axis corresponds to the pumping variables. Variables 1–8 correspond to pumping from the production wells P1–P8 for the time period 1 and 9–11 correspond to pumping from the barrier wells B1–B3 for the first time period. Similarly 12–19 and 20–22 correspond to production well and barrier well pumping for second time period and 23–29 and 30–33

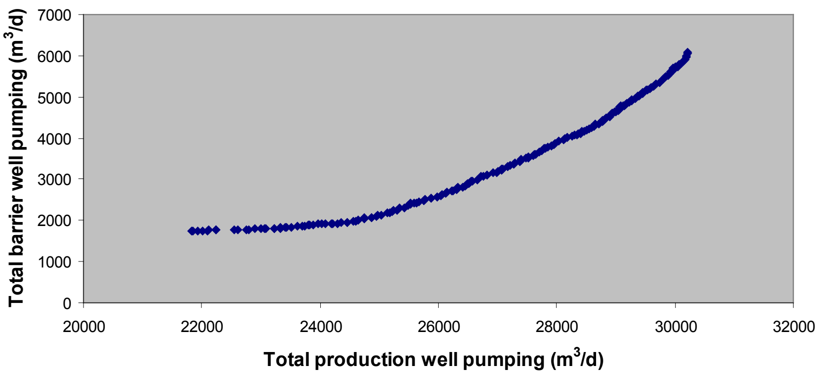

Fig. 2. Pareto-optimal set of solutions for the well field management problem.

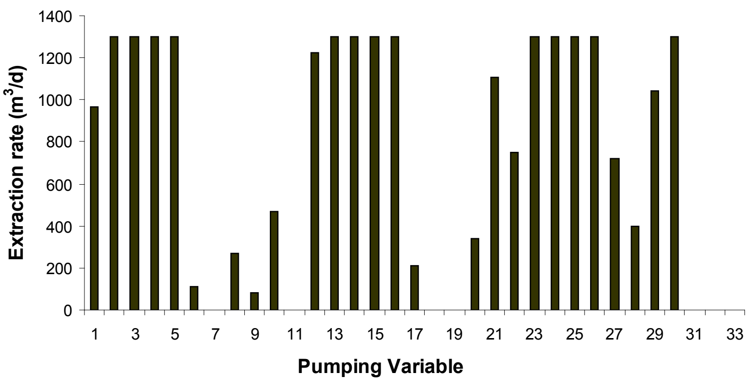

Fig. 3. Optimal pumping rates corresponding to total barrier well pumping of 2037 m^3/d.

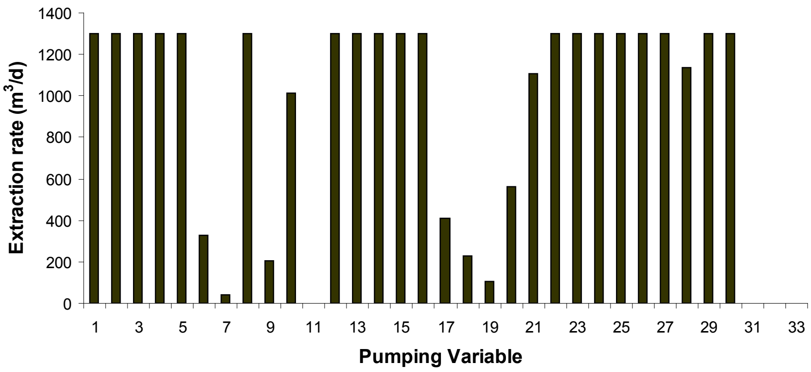

Fig. 4. Optimal pumping rates corresponding to total barrier well pumping of 3094 m^3/d.

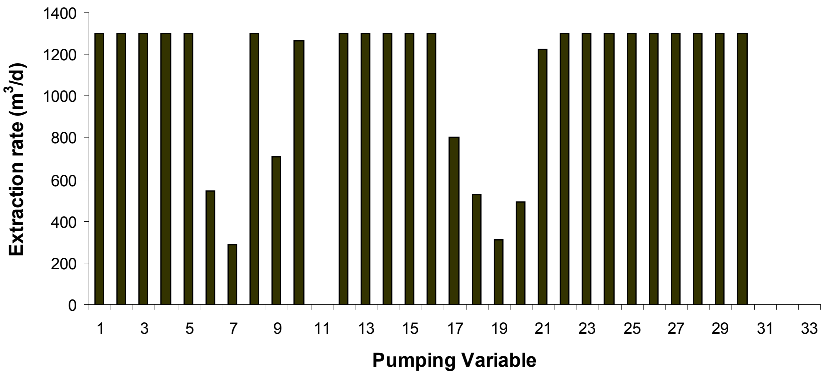

Fig. 5. Optimal pumping rates corresponding to total barrier well pumping of 4121 m^3/d.

correspond to the same for third time period. Figs. 3, 4 and 5 corresponds to the optimal solutions (24349, 2037), (27634, 3094) and (28291, 4121) respectively. By simulating the aquifer processes for the optimal solutions obtained using the management model, it was found that the salinity concentrations at the monitoring locations M1, M2 and M3 at the end of the management time period were limited to the maximum limit prescribed in the management model. Thus the methodology is efficient in obtaining optimal strategies for operating saltwater intruded well fields.

8. Conclusion

A methodology for the simultaneous determination of optimal rates of pumping from the production bores and barrier wells of a coastal aquifer well field is developed and tested. The goal of the management strategy is to control the saltwater intrusion into the aquifer. The methodology uses a finite element based simulation model, a neural network based meta-model and a multi-objective genetic algorithm. The multi-objective optimal solutions for the well field management problem were derived using the linked simulation-optimization methodology. The optimal solutions prescribe the rates at which the production bores and barrier wells in the well field be operated for a three year management time period. The rates of pumping a particular well within a time period of one year were considered constant. It was found that, by operating the wells as prescribed by the management model, the saltwater intrusion can be confined to pre-specified limits. Thus the developed methodology can be used to derive optimal operation strategies for the combined operation of production bores and barrier wells in a saltwater intrusion affected well field for sustainable use of coastal aquifers.

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References

[1] Report of the United Nations Commission on Sustainable Development Agenda 21: Chap. 17.3, 1992. URL: http://www.un.org/esa/dsd/index.shtml.

[2] J. Bear, A.H.D. Cheng, S. Sorek, D. Ouazar and I. Herrera, Seawater Intrusion in Coastal Aquifers — Concepts, Methods and

Practices, Kluwer Academic Publishers, 1999.
[3] M. Maimone, Developing an effective coastal aquifer management program, Proc. 17th Saltwater Intrusion Meeting, Delft, The Netherlands, 2002, pp. 327–336.
[4] H.R. Henry, Salt intrusion into freshwater aquifers, J. Geophys. Res., (1959) 1911–1919.
[5] J. Bear and G. Dagan, Some exact solutions of interface problems by means of the hodograph method, J. Geophys. Res., 8 (1964) 1563–1572.
[6] M.S. Hantush, Unsteady movement of freshwater in thick unconfined saline aquifers, Bull. Int. Assoc. Sci. Hydrol., 2 (1968) 40–60.
[7] S. Schmorak and A. Mercado, Upcoming of freshwater-seawater interface below pumping wells, field study, Water Resources Res., 5 (1969) 1290–1311.
[8] P.C. Sikkema and J.C. Van Dam, Analytical formulae for the shape of the interface in a semi-confined aquifer, J. Hydrology, 3–4 (1982) 201–220.
[9] G. Dagan and D.G. Zeitoun, Seawater-freshwater interface in a stratified aquifer of random permeability distribution, J. Contaminant Hydrology, 3 (1988) 185–203.
[10] A. Naji, D. Ouazar and A.H.D. Cheng, Locating the saltwater-freshwater interface using non-linear programming and h-adaptive BEM. Eng. Analysis Boundary Elements, 3 (1998) 253–259.
[11] A. Mantoglou, M. Papantoniou, and P. Giannoulopoulos, Management of coastal aquifers based on non-linear optimization and evolutionary algorithms, J. Hydrology, 1–4 (2004) 209–228.
[12] S. Sorek and G.F. Pinder, Survey of computer codes and case histories, In Seawater Intrusion in Coastal Aquifers — Concepts, Methods and Practices, Kluwer Academic Publishers, 1999.
[13] A. Dhar and B. Datta, Saltwater intrusion management of coastal aquifers — I: linked simulation-optimization, J. Hydrol. Eng., 12 (2009) 1263–1272.
[14] C.I. Voss, A finite-element simulation model for saturated-unsaturated, fluid-density –dependent groundwater flow with energy transport or chemically reactive single-species solute transport, US Geological Survey Water Resources Investigations Report, 1984, 84-4369.
[15] H.C.J. Lin, D.R. Richards, C.A. Talbot, G.T. Yeh, J.R. Cheng and N.L. Jones, A three-dimensional finite element computer model for simulating density-dependent flow and transport in variable saturated media: Version 3.0, US Army Engineering Research and Development Centre, 1997.
[16] W. Guo, and C.D. Langewin, User's guide to SEAWAT: a computer program for simulation of three-dimensional variable-density groundwater flow, USGA Open File Report 01-434, 2002.
[17] K.L. Kipp, HST3D, a computer code for simulation of heat and solute transport in three dimensional groundwater flow systems, USGS Water Resources Investigations Report 86-4095, 1986.
[18] K.L. Jr. Kipp, Guide to the revised heat and solute transport simulator, HST3D-Version 2, USGS Water Resources Investigation Report 97-4157, 1997.
[19] H.J.G. Diersch, FEFLOW finite element subsurface flow and transport simulation system reference manual, WASY Inst. For Water Resour. Plann. And Syst. Res., Berlin, 2002.
[20] A.D. Cheng, D. Halhal, A. Naji, and D. Ouazar, Pumping optimization in saltwater intruded coastal aquifers, Water Resources Res., 8 (2000) 2155–2165.
[21] A. Mantoglou, Pumping management of coastal aquifers using analytical models of saltwater intrusion, Water Resources Res., 12 (2003) .
[22] C. Park and M. Aral, Multi-objective optimization of pumping rates and well placement in coastal aquifers, J. Hydrology, 1–2 (2000) 80–99.
[23] R. Willis and B.A. Finney, Planning model for optimal control of saltwater intrusion, J. Water Resources Plan. Manage., 2 (1988) 163–178.
[24] B.A. Finney, S. Samsuhadi and R. Willis, Quasi-three-dimensional optimization model for Jakarta basin, J. Water Resources Plan. Manage., 1 (1992) 18–31.
[25] P.G. Emch and W.W.G. Yeh, Management model for conjunctive use of coastal surface water and groundwater J. Water Resources Plan. Manage. 3 (1998) 129–139.
[26] S. Rao, S. Bhallamudi, B. Thandaveswara and G. Mishra, Conjunctive use of surface and groundwater for coastal and deltaic systems, J. Water Resources Plan. Manage., 3 (2004) 255–267.
[27] A. Mantoglou and M. Papantoniou, Optimal design of pumping networks in coastal aquifers using sharp interface models, J. Hydrology, 1–2 (2008) 52–63.
[28] K. Qahman, A. Larabi, D. Ouazar, A. Naji and A.H.D. Cheng, Optimal and sustainable extraction of groundwater in coastal aquifers, Stochastic Environ. Res. Risk Assess., 2 (2005) 99–110.
[29] A. Das and B. Datta, Development of multi-objective management models for sustainable use of coastal aquifers, J. Irrigation Drainage Eng., 3 (1999) 112–121.
[30] S. Ranjithan, J.W. Eheart and J.H. Garrett, Neural network based screening for groundwater reclamation under uncertainty, Water Resources Res., 3 (1993) 563–574.
[31] A.h. Aly and R.C. Peralta, Optimal design of aquifer cleanup systems under uncertainty using a neural network and a genetic algorithm, Water Resources Res,, 8 (1999) 2523–2532.
[32] S.Q. Yan and B. Minsker, Optimal groundwater remediation design using an Adaptive Neural Network Genetic Algorithm, Water Resources Res., 5 (2006).
[33] R.K. Bhattacharya, and B. Datta, Optimal management of coastal aquifer using linked simulation optimization approach, Water Resources Manage., 3 (2005) 295–320.
[34] G. Kourakos and A. Mantoglou, Pumping optimization of coastal aquifers based on evolutionary algorithms and surrogate modular neural network models, Adv. Water Resources, 4 (2009) 507–521.
[35] K. Deb, Multi-Objective Optimization Using Evolutionary Algorithms, John Wiley and Sons Ltd, 2001.