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Review: Simulation-optimization models for the management and monitoring of coastal aquifers

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Abstract The literature on the application of simulation-optimization approaches for management and monitoring of coastal aquifers is reviewed. Both sharp- and dispersive-interface modeling approaches have been applied in conjunction with optimization algorithms in the past to develop management solutions for saltwater intrusion. Simulation-optimization models based on sharp-interface approximation are often based on the Ghyben-Herzberg relationship and provide an efficient framework for preliminary designs of saltwater-intrusion management schemes. Models based on dispersive-interface numerical models have wider applicability but are challenged by the computational burden involved when applied in the simulation-optimization framework. The use of surrogate models to substitute the physically based model during optimization has been found to be successful in many cases. Scalability is still a challenge for the surrogate modeling approach as the computational advantage accrued is traded-off with the training time required for the surrogate models as the problem size increases. Few studies have attempted to solve stochastic coastal-aquifer management problems considering model prediction uncertainty. Approaches that have been reported in the wider groundwater management literature need to be extended and adapted to address the challenges posed by the stochastic coastal-aquifer management problem. Similarly, while abundant literature is available on simulation-optimization methods for the optimal design of groundwater monitoring networks, applications targeting coastal aquifer systems are rare. Methods to optimize compliance monitoring strategies for coastal aquifers need to be developed considering the importance of monitoring feedback information in improving the management strategies.

Keywords Groundwater management · Groundwater monitoring · Optimization · Numerical modelling · Salt-water/fresh-water relations

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Introduction

Land areas adjacent to the world's shorelines support a large and ever-increasing concentration of human population, settlements and socio-economic activities, including many of the world's large cities. About half of the world's population live within 200 km of a coastline and the average population density in coastal areas is about twice the world's average population density (Creel 2003). Due to the hydraulic continuity with the sea, coastal aquifers are susceptible to salinity intrusion. Due to the density dependence of the mixing, saltwater intrusion in coastal aquifers is a highly non-linear and complex process (Bear et al. 1999). The mixing zone or transition zone has varying thickness 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 an upward and/or inland direction (Bear et al. 1999). This large-scale displacement can be caused by factors including groundwater abstraction, sea level changes, recharge reduction and land reclamation and excavation.

To study the effects of different withdrawal strategies on the aquifer salinity the aquifer system needs to be reliably simulated. A historical perspective of simulation of saltwater intrusion in coastal aquifers is provided by Reilly and Goodman (1985). Books by Holzbecher (1998) and Bear et al. (1999) and fundamental papers by others (Huyakorn et al. 1987; Galeati et al. 1992; Putti and Paniconi 1995) provide insight into the advective-dispersive flow and transport phenomena of saltwater intrusion in coastal aquifer systems. The modeling approaches used for simulation of flow and transport in coastal aquifers include: (1) sharp-interface modeling and (2) dispersive interface (density dependent) modeling. Detailed analysis of the theoretical developments and implementation of these two modeling approaches have been described in detail elsewhere (Werner et al. 2013) and is not repeated here. Werner et al. (2013) provides a recent review of the research on seawater intrusion process, investigation and management. The readers are directed to that study for an in-depth review of research on the hydrogeological, hydrochemical and climatic processes associated with saltwater intrusion. Werner et al. (2013) also reviews different measurement and prediction approaches for seawater intrusion process.

Sustainable use of coastal aquifers requires design and implementation of well-planned management strategies. Simulation-optimization approaches using groundwater models have been extensively used in the past to optimize the pump-and-treat management of contaminated aquifers and landfills (Gorelick 1983; Bayer et al. 2010; Mantoglou and Kourakos 2007). Similar approaches have been extended to optimal management of coastal aquifers in the recent past. One possible way of controlling the saltwater intrusion and optimally managing coastal aquifers is to determine and implement optimal temporally and spatially varying groundwater withdrawal strategies to ensure sustainable use of freshwater from the aquifer. In addition, prescription and implementation of management strategies require effective and efficient monitoring of the implemented strategy for compliance and to detect any deviation from the stated goals.

This study reviews the development and application of simulation-optimization based approaches for optimal and sustainable management of coastal aquifers. The utility of monitoring feedback based on implementation of a coastal aquifer management strategy is also elucidated. The remaining sections of the paper review the simulation-optimization approach for saltwater intrusion management and different techniques that have been developed for implementing the same, describe stochastic simulation-optimization approaches for groundwater management considering uncertainty in the simulation models, give a brief review of different optimization-based groundwater monitoring network design approaches, introduce the compliance monitoring feed-back based adaptive management, and present the conclusions.

Simulation-optimization approach

While numerical simulation models are used to evaluate the effect of different management alternatives on the aquifer system, an optimal management strategy cannot be identified by sequentially evaluating different pumping (or other management) schemes, as there are infinite combinations of plausible alternative withdrawal strategies, even for an identified sustainable total extraction rate from the aquifer. The distribution of the permissible total extraction amongst different wells is also important, as local saltwater up-coning could result from a high extraction rate even in a single or a couple of wells. Optimization algorithms are used in a coupled simulation-optimization framework to identify the optimal management strategy for coastal aquifers. The optimization algorithm performs an organised search for new and improved pumping schemes or other management alternatives. During this search process, the simulation model is evaluated many times to quantify the impact of the pumping scheme on the movement of the saltwater front.

Gorelick (1983) gives a detailed review of coupled simulation-optimization models for groundwater management. The study classified the groundwater management models into two categories—the groundwater hydraulic management model and the groundwater policy evaluation and allocation model. The simulation-optimization modeling reported in this study pertains to the groundwater hydraulic management models. Groundwater hydraulic management simulation-optimization approaches are characterized by the incorporation of the simulation model as a constraint in the optimization model. The different simulation-optimization approaches that have been used to accomplish this include the embedding approach, the response matrix approach, the external linking of the groundwater model with the optimization algorithm and the surrogate model based approach. These approaches have been adopted for a variety of groundwater management problems including pump-and-treat optimization, groundwater contamination detection and monitoring network design. Similar methods were also later adapted for coastal aquifer management. While the methodology essentially remains the same, application of simulation-optimization for coastal aquifer management has the additional challenge resulting from the increased nonlinearity of the problem caused by the coupled flow and transport (Bear et al. 1999).

The earliest attempts to develop simulation-optimization models for groundwater management considered either incorporating the flow and transport equations as constraints in the optimization code (embedding approach) or approximating the responses of the groundwater model using a linear response matrix generated by running the groundwater model multiple times (response matrix approach)—examples of the embedding approach for groundwater management include Aguado and Remson 1974, Alley et al. (1976), Willis and Finney (1988) and Culver and Shoemaker (1993). Das and Datta (1999a, b) provided an example of the implementation of the embedding approach for coastal aquifer management. Although the embedding approach provided a rigorous method to solve the non-linear optimization based management models, it was constrained by computational and convergence issues for large-scale practical applications. The response matrix approach relied on the linear superposition of unit responses (Gorelick 1983). In this approach, a linear response matrix is developed by multiple runs of the numerical simulation model to obtain the aquifer

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responses to unit stresses. Groundwater management models developed based on a response matrix approach include Deininger (1970), Maddock (1972, 1974), Rosenwald and Green (1974), Heidari (1982) and Willis (1983). The response matrix approach was applied for coastal aquifer management by Hallaji and Yazicigil (1996). They considered seven different groundwater management models to determine the optimal pumping policy for a coastal aquifer in southern Turkey threatened by saltwater intrusion. The linearity assumption, which formed the core of the response matrix approach, precluded its application to nonlinear groundwater management problems.

Simulation optimization by external linking

Compared to embedding, an improved approach of simulation-optimization is achieved by coupling the simulation model externally with the optimization algorithm. In this way, the simulation model becomes a subroutine or sub-program supplying only the necessary variables to the optimization algorithm rather than considering all the partial differential equations of flow and mass transport as constraints of the optimization problem, as in the embedding approach. Thus, the solution and convergence of the simulation model no longer becomes a challenge for the optimization algorithm but, instead, happens external to the optimization problem. Models using different approaches to simulate density-dependent transport have been used in the externally coupled simulation-optimization models to derive optimal coastal and contaminated aquifer management strategies, including analytical models, numerical sharp-interface models, numerical density-dependent models and surrogate models. From the studies reported to have used this approach for optimal groundwater management, including real world applications, this approach is a more preferred and practical approach over the embedding or response matrix approach.

Recently developed management models with analytical solutions for the saltwater intrusion process include Cheng et al. (2000), Mantoglou (2003) and Park and Aral (2004). While a genetic algorithm was used by Cheng et al. (2000) and Park and Aral (2004), Mantoglou (2003) used sequential quadratic programming as the optimization algorithm. These studies developed on the concept of single potential formulation of Strack (1976). Numerical simulations using the sharp-interface approach have been used by Willis and Finney (1988), Finney et al. (1992), Emch and Yeh (1998), Rao et al. (2003, 2004a), and Mantoglou and Papantoniou (2008). Shi et al. (2011) used a numerical sharp-interface model to determine saltwater and freshwater withdrawal rates at a pumping well.

Density-dependent flow and transport models have been increasingly used to solve coastal aquifer management problems (Das and Datta 1999a, b; Qahman et al. 2005; Dhar and Datta 2009a, b; Katsifarakis and Petala 2006; Abd-Elhamid and Javadi 2011). Whereas linear and non-linear classical optimization techniques were used in the early days, there is an increasing trend in the use of heuristic optimization techniques often based on evolutionary principles. These include single and multi-objective genetic algorithms (Bhattacharjya and Datta 2005; Qahman et al. 2005; Dhar and Datta 2009a, b, c; Sreekanth and Datta 2011c; Sreekanth et al. 2012; Sreekanth 2012) simulated annealing (Roa et al. 2004a,b), evolutionary simplex schemes (Kourakos and Mantoglou 2009), elitist ant colony optimization (Ataie-Ashtiani and Ketabchi 2011) and particle swarm optimization (Gaur et al. 2011). A comprehensive diagnostic assessment of the evolutionary multi-objective evolutionary algorithms for water resources can be found in Reed et al. (2013). Papadopoulou (2011) reports a review of different optimization approaches applied in developing management methodologies for the control of saltwater intrusion in coastal aquifers. Some of these studies used surrogate models to substitute the density-dependent model within the optimization model.

Details of 10 representative studies applying simulation-optimization models for coastal aquifer management are compared in Table 1. All the simulation-optimization models were developed based on an analytical solution for seawater-intrusion-considered assumptions like semi-infinite extent of the aquifer, homogeneity and isotropy. These were the essential simplifications of the problem required to apply analytical solution techniques. Despite the simplicity, these approaches were found to approximate the physics behind the saltwater intrusion process and, thus, were considered useful for conducting feasibility studies and/or preliminary design (Cheng et al. 2000). Numerical solution of the sharp-interface flow problem with popular codes like MODFLOW has been found to overcome such restrictions. It is expected that the validity of the solutions obtained by the sharp-interface-model-based simulation-optimization is subject to the conditions imposed by the assumptions of the sharp-interface and Ghyben-Herzberg relationship.

While comprehensive simulation of the saltwater intrusion process can be simulated using density-dependent numerical models, often the scarcity of the required data pertaining to the boundary conditions, mixing zone, aquifer geometry etc., constrain the development of such models (Sanford and Pope 2010). Also, simulation-optimization using a density-dependent flow and transport model is challenged by the computational requirement for the optimization runs. Although, the computer time reported by different studies cannot be directly compared, the necessity to solve the flow and transport equations simultaneously necessitates much larger computer time for density-dependent models over the sharp-interface models. Wherever compared, the optimization based on evolutionary algorithms required more computing resource than the traditional optimization approaches. For the evolutionary algorithms, the computational requirement is proportional to the number of variables of optimization (dimension of solution space). Amongst the studies that used 3D density-dependent models for simulation optimization only 2 considered more than 30 variables for optimization. It is noteworthy that while Sedki and Ouazar (2011) considered 184

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Table 1 Sharp-interface and density-dependent models used for simulation-optimization

Reference	Simulation model details	Optimization	Objectives	Maximum variables/ dimension of solution space	Remarks on computational time	Aquifer characteristics
Sharp-interface models						
Cheng et al. (2000)	Ghyben-Herzberg relation, Strack (1976) potential	GA	Pumping rate	15	6 h	Semi-infinite aquifer, homogeneity
Mantoglou (2003)	Ghyben-Herzberg relation, Strack (1976) potential	SQP, LP	Pumping rate, location	5	SQP>LP	Finite but simplified geometry, homogeneity
Park and Aral (2004)	Ghyben-Herzberg relation, Strack (1976) potential	GA	Pumping rate	8	30 min	Semi-infinite geometry, homogeneity
Mantoglou et al. (2004)		EA, EA+SQP	Pumping rate	11	EA>SQP	Simplified geometry
Mantoglou and Papantoniou (2008)	Ghyben-Herzberg relation, Strack potential, MODFLOW	EA, EA+SQP	Pumping rate, welllocations	11	EA>EA+SQP	Complex geometry, heterogeneity
Density-dependent models						
Das and Datta (1999a, b)	Authors' own code	Classical optimization	Pumping rate	8	10 h	Simple hypothetical
Qahman et al. (2005)	CODESA-3D	GA	Pumping rate	4	Several hours	Simple hypothetical
Dhar and Datta (2009a, b, c)	FEMWATER	MOGA	Pumping rate	33	30 days	Hypothetical
Kourakos and Mantoglou (2009)	SEAWAT	EASS	Pumping rate	34	9.5 days	Real aquifer, heterogeneous
Sedki and Ouazar (2011)	MODFLOW	GA	Pumping rate	184	5 h 45 min	Real aquifer, heterogeneous, transport was not simulated

GA genetic algorithm; *EA* evolutionary algorithm; *SQP* sequential quadratic programming; *LP* linear programming; *MOGA* multi-objective genetic algorithm; *EASS* evolutionary annealing simplex scheme

variables in simulation-optimization, saltwater intrusion was not explicitly simulated in that study. Instead, constraints on the hydraulic head near the coast were specified to prevent saltwater intrusion. While studies based on the sharp-interface approach have explored the optimization of well locations, studies based on 3D density-dependent models have not yet explored optimization of well locations. Evidently, the computational burden poses a real challenge to the application of density-dependent simulation-optimization models to regional-scale aquifer systems with large numbers of wells. Often computational burden may be reduced if the aquifer could be modelled as a 2D system.

As evident from the foregoing discussion, both the modelling approaches have their own advantages and disadvantages when used in the simulation-optimization framework; thus, the simulation model needs to be carefully chosen before the development of the management model considering a number of factors. These include the aquifer geometry, whether the aquifer can be represented as a 2D vertical or 2D areal model (to invoke Dupit-Forchheimer approximation), whether the mixing zone is thin relative to the aquifer thickness, whether the flow rates into the saltwater zone are small, objective of the management model, etc. For example, if the objective is a preliminary assessment of a proposed pumping (and/or recharge) scheme a sharp-interface-based simulation-optimization may be sufficient. Whereas, if one needs to precisely simulate the concentration contours around an optimally pumped well in the mixing zone, a very fine-scaled density-dependent model may be necessary.

Surrogate models for simulation-optimization

Surrogate models are used in coupled simulation-optimization models for groundwater management essentially to reduce the computational burden involved in repeated groundwater model runs corresponding to different candidate solutions in the optimization search (Rao et al. 2003). Substantial research work has been done on using artificial neural networks (ANN) as surrogate models for simulation-optimization studies. Razavi et al. (2012) gives an extensive review of the use of surrogate models in water resources modeling. In this work, the focus is limited to selected applications of surrogate modeling methods for optimal coastal aquifer management (Table 2).

ANNs were introduced as surrogate models for groundwater simulation in the early 1990s (Ranjithan et al. 1993; Rogers et al. 1995; Aly and Peralta 1999). Rao et al. (2003) used ANN with the sharp-interface saltwater intrusion model SHARP (Essaid 1990) to identify optimal pumping locations and rates. The management model was solved as a non-linear, non-convex, combinatorial problem using a simulated

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Table 2 Surrogate modeling based simulation-optimization studies for coastal aquifer management

Reference	Surrogate model[a]	ANN or GP architecture[b]	No. of patterns	Training procedure	Simulation model
Offline training					
Rao et al. (2003)	ANN	3 layers	5,000	Off-line, single training	SHARP
Rao et al. (2004a, b)	ANN	24-6-6	4,900	Off-line, single training	SEAWAT
Bhattacharjya and Datta (2005)	ANN	18-x-18	2,400	Off-line, single training	Numerical model
Bhattacharjya et al. (2007)	ANN	24-x-14	636	Off-line, single training	FEMWATER
Nikolos et al. (2008))	ANN	5-x-22	3,125	Off-line, single training	PTC
Dhar and Datta (2009a)	ANN	33-66-24	3,600	Off-line, single training	FEMWATER
Ataie-Ashtiani et al. (2013)	ANN	11-40-20	56	Offline, single training	SUTRA
Adaptive training					
Kourakos and Mantoglou (2009)	ANN, MNN	34-34-34 34-34-1 (34 modules)	273	Online training	SEAWAT
Papadopoulou et al. (2010)	RBFN	5-53-1	80	Online training	PTC
Sreekanth and Datta (2010)	MNN	33-33-1 (33 modules)	230	Offline, two-stage adaptive training	FEMWATER
Sreekanth and Datta (2011a, b)	Genetic programming	33-1 (33 modules)	230	Offline, two-stage adaptive training	FEMWATER
Kourakos and Mantoglou (2013)	Modular neural network	34-34-1	40 samples each generation	Online, adaptive training	SEAWAT

[a] *ANN* artificial neural network, *RBFN* radial basis function network, *MNN* modular neural network

[b] Input-hidden-output architecture for ANN and Input–output for GP model

x number of neurons in the hidden layer varies based on the problem complexity

annealing algorithm for optimization. A number of recent studies have used ANN to replace density-dependent saltwater intrusion model in simulation-optimization (Rao et al. 2004a; Bhattacharjya and Datta 2005, 2009; Bhattacharjya et al. 2007; Dhar and Datta 2009a; Nikolos et al. 2008; Kourakos and Mantoglou 2009, 2013; Behzadian et al. 2009; Sreekanth and Datta 2010; Papadopoulou et al. 2010; Ataie-Ashtiani et al. 2013). Sreekanth and Datta (2010, 2011a) developed genetic programming-based (Koza 1994) surrogate models to substitute 3D density-dependent flow and transport models for simulating pumping-induced saltwater intrusion processes within an optimization framework. Other popular surrogate models used in conjunction with groundwater simulation-optimization include radial basis functions (Regis and Shoemaker 2004, 2007, 2009; Mugunthan et al. 2005; Mugunthan and Shoemaker 2006; Castelletti et al. 2010) and Kriging (Bau and Mayer 2008; Hemker et al. 2008; di Pierro et al. 2009); however, these surrogate modeling approaches are yet to be explored for solving coastal aquifer management problems.

The surrogate models described in the preceding section belong to the broad category of data-driven models considering that these models are trained based on the input–output patterns obtained from the physically based models. The number of patterns required to train the surrogate model varies depending on the dimension of solution space, complexity of the problem and a variety of other factors. Numbers or patterns as small as 56 (Ataie-Ashtiani et al. 2013) have been reported to be sufficient to emulate the response surface. One commonly used approach found in the seawater-intrusion-management context is the development of a global surrogate model based on a pre-generated set of training data (input–output patterns). In this case, the training is performed offline, i.e., separate from the optimization search, and all the function evaluations during optimization are carried out using the surrogate model (Rao et al. 2004a; Bhattacharjya and Datta 2005, 2009; Bhattacharjya et al. 2007; Dhar and Datta 2009a). A major drawback of this approach is that as the number of inputs and outputs increases, the number of patterns required to adequately train the surrogate model also increases. The time required to train the surrogate model also increases opposing the purpose of surrogate modeling.

Two solutions have been proposed to overcome this difficulty. The first one is the development of individual modules of the surrogate model targeting specific outputs. The advantage of this method is that the parameters (connection weights) of each module could be optimized independently of the other. The second is performing an adaptive training of the surrogate model in the vicinity of the search as optimization proceeds. Adaptive training permits to sequentially update the surrogate model based on the increasing number of training patterns available as the optimization proceeds. Development of modular surrogate models (Kourakos and Mantoglou 2009, 2013) and adaptive training of surrogate models (Papadopoulou et al. 2010) have both been found to be helpful to increase the efficiency of the surrogate modeling based simulation-optimization for coastal aquifer management. The adaptive training may be performed either offline (Sreekanth and Datta 2010) or online (Papadopoulou et al. 2010; Kourakos and Mantoglou 2013).

The utility of these approaches varies depending on the simulation-optimization problem. For instance, when the dimension of solution space (number of state variables) is less and the aquifer system being simulated is small, it may be advantageous to have one global surrogate model approximating the response of the whole aquifer system. This helps to avoid training of multiple surrogate models

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or retraining the surrogate model during the optimization process. On the other hand, when the dimensionality of the search space is huge, it may be best to develop independent modules of the surrogate model and retrain them as optimization proceeds to adapt the model to the spatial dynamics of the response function.

In addition to the 'data-driven' approaches, 'model-driven' surrogate models also have been used to reduce the computational burden of simulation optimization. The 'model-driven' surrogate modeling is based on the development of less cumbersome physically based models. McPhee and Yeh (2008) illustrated the application of reduced models for simulation-optimization based groundwater management. No studies specific to coastal aquifer management have been reported in this domain.

A number of studies have reported the application of surrogate-modeling-based simulation-optimization for the optimization of pumping rates in coastal aquifers; however, optimization of well location using surrogate modeling approaches has not been reported. One major challenge in this regard is the increase in dimensionality of the search space when well locations are also included as state variables. A detailed discussion of the disadvantages of surrogate modeling for water resources application can be found in Razavi et al. (2012). Within the specific context of surrogate modeling for groundwater simulation optimization, the major drawbacks include dimensionality, difficulty in handling discrete variables, loss of accuracy incurred in replacing the numerical model with the surrogate, difficulty in handling numerical model uncertainty and additional uncertainty resulting from the use of surrogate model.

Optimal groundwater management under numerical and surrogate model uncertainty

Different stochastic optimization techniques have been used in the past for optimal decision making under uncertainty for other groundwater management applications (Wagner and Gorelick 1987; Tiedeman and Gorelick 1993; McPhee and Yeh 2006). The main goal of a stochastic simulation-optimization model is to identify reliable optimal solutions for groundwater management. Chance-constrained programming had been used in groundwater management by Wagner and Gorelick (1987, 1989), Morgan et al. (1993), and Datta and Dhiman (1996). Benhachmi et al. (2003) applied a chance-constrained modeling approach for pumping optimization in a saltwater-intruded coastal aquifer. Another method for stochastic simulation optimization is the multiple-realisation approach (Wagner and Gorelick 1989; Morgan et al. 1993; Chan 1993; Feyen and Gorelick 2004, 2005; Bayer et al. 2008). In this method, a number of realisations of the uncertain model parameters are considered simultaneously in a simulation-optimization formulation to identify the optimal solution. The reliability of the identified solution is often tested by means of Monte Carlo simulations outside the simulation-optimization model.

Recent studies reporting stochastic simulation-optimization approaches include Bayer et al. (2008), Singh and Minsker (2008), Bau and Mayer (2008), Kourakos and Mantoglou(2008), Qin and Huang (2009) and Parker et al. (2010). Identifying the most critical realizations (Ranjithan et al. 1993) of the uncertain parameter fields and incorporating them in the multiple realization approach can help reduce the computational burden of the stochastic optimization problem. A few recent studies have implemented such approaches for groundwater management (Mantoglou and Kourakos 2007; Kourakos and Mantoglou 2008; Bayer et al. 2008, 2010). Only a few studies have attempted to use surrogate models in an uncertainty framework to derive reliable solutions for groundwater management. Aly and Peralta (1999) developed an ANN-based surrogate modeling framework to optimize the design of a pump-and-treat system for aquifer clean up considering uncertainty in hydraulic conductivity. He et al. (2010a, b) used a set of proxy simulators, in a coupled simulation-optimization model for groundwater remediation design under parameter uncertainty of the proxy simulators. Yan and Minsker (2010) presented an applied dynamic surrogate models with noisy genetic algorithms to optimize groundwater remediation designs in an approach where they used ANN surrogate models to predict the posterior expectations on the basis of stochastic decision theory. Sreekanth and Datta (2011b) used an ensemble of surrogate models based on genetic programming to quantify the predictive uncertainty and use it in a multiple realization optimization framework to derive reliable solutions for coastal aquifer management. It was found that reliability of the resulting solutions using the multiple realization approach was much greater than using a single deterministic model within the simulation-optimization framework.

Not many studies have dealt with coastal aquifer management considering the prediction uncertainty of the simulation model. Modeling saltwater intrusion as a stochastic problem was initiated by Dagan and Zeitoun (1998a, b) in which the aquifer was assumed to have horizontal layers with random hydraulic conductivities. Naji et al. (1998) developed analytical solutions for saltwater intrusion considering uncertainty in hydrogeologic and pumping conditions, whereby they used an optimization approach to identify the saltwater interface location considering uncertainty in the input parameters using a boundary element method. These were sharp-interface studies based on the Strack potential. Prieto et al. (2006) investigated the general effects of temporally random boundary conditions on seawater intrusion by stochastic simulation of groundwater flow and transport dynamics. Pumping optimization in a stochastic setting was not considered in any of these studies. Koussis et al. (2010a, b) gives a fine example of application of stochastic optimization for the economic management of coastal aquifers considering desalination and artificial recharge of treated wastewater to control saltwater intrusion. They compared the deterministic solutions to the stochastic solutions and identified that

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the deterministic solutions were more conservative and yielded higher salinity at the pumping wells. Sreekanth and Datta (2014) explored the potential of extending the ensemble surrogate modeling approach for pumping optimization in coastal aquifer considering uncertainty in the hydraulic properties. Rajabi and Ataie-Ashtiani (2014) illustrated the use of optimized Latin hypercube sampling strategies for uncertainty analysis of seawater intrusion simulation.

This review has revealed the low volume of literature on application of stochastic simulation-optimization models for the management of coastal aquifers. Stochastic optimization techniques for management of uncertain systems are used more commonly in the wider groundwater literature. However, their adaptation for coastal aquifer management is challenged mainly by the increased computational burden involved in the simulation of coupled flow and transport for coastal aquifer systems; hence, research efforts need to focus on developing and applying efficient methods for uncertainty characterisation. Methods like the critical realization approach (Kourakos and Mantoglou 2008; Bayer et al. 2008) could readily be employed for solving stochastic-coastal-aquifer-management problems. Where this is computationally prohibitive, deterministic optimization may be applied and further the uncertainty of the deterministic solutions may be tested using Monte-Carlo approaches; additionally, where applicable, use of sharp-interface models together with stochastic optimization approaches needs to be further explored. Adaptation of surrogate modeling techniques for coastal aquifer management under uncertainty also needs to be further developed.

Optimal compliance monitoring and feed-back information

Even though the reliability of management solutions can be enhanced by accounting for uncertainty as described in section 'Optimal groundwater management under numerical and surrogate model uncertainty', it is still possible that the responses of the complex groundwater systems to an implemented groundwater management strategy deviate from their simulated counterpart. However complex the groundwater model is, it is still essentially a simplified approximation of the complex real world groundwater system; hence it is very important to monitor the compliance of the aquifer responses to the implementation of an optimal groundwater management strategy. Monitoring of aquifer systems specifically with a target to capture the aquifer changes resulting from a proposed or currently operating groundwater management project is called compliance monitoring.

Monitoring is important for any groundwater management project. Design of an optimal monitoring network assumes greater importance due to the cost involved in the water quality monitoring and the inherent uncertainty in the contaminant plume movement. A comprehensive review of saltwater intrusion monitoring in coastal aquifers was given in Melloul and Goldenberg (1997) and Barlow and Reichard (2010). Melloul and Goldenberg (1997) recommended a combination of geo-physical methods and direct well observations as an optimal means of assessing seawater intrusion in coastal aquifers. Monitoring concentrations by direct well observations is expensive as implementation of new wells and periodic sampling and analysis are involved; hence, optimal design of the monitoring network is required to efficiently and economically monitor saltwater intrusion and the compliance with the optimal strategies of management.

Loaiciga et al. (1992) report a comprehensive review of groundwater monitoring network design. Zhang et al. (2005) classified the quantitative approaches for monitoring network design into three broad classes: (1) stochastic simulation approaches (Ahlfeld and Pinder 1992; Massmann and Freeze 1987a, b; Meyer and Brill 1988; Meyer et al. 1989; (2) variance-based approaches (Rouhani 1985; Graham and McLaughlin 1989a, b; Van Geer et al. 1991; Bierkens et al. 2001; Herrera and Pinder 2005) and (3) optimization-based approaches.

Many optimization-based approaches for monitoring network design have been reported in the literature. Different objectives of optimization for designing monitoring network include minimisation of prediction variance (McKinney and Loucks 1992; Asefa et al. 2004, 2005; Nunes et al. 2004a, b, c; Herrera and Pinder 2005; Ammar et al. 2008; Chadalavada and Datta 2008; Dokou and Pinder 2009; Ruiz-Cardenas et al. 2010; Chadalavada et al. 2011), contaminant detection (Massmann and Freeze 1987a, b; Meyer and Brill 1988; Hudak and Loaiciga 1992, 1993; Datta and Dhiman 1996; Mahar and Datta 1997; Storck et al. 1997; Montas et al. 2000; Reed et al. 2000; Reed and Minsker 2004; Dhar and Datta 2007; Kollat et al. 2008; Bashi-Azghadi and Kerachian 2010), minimisation of monitoring cost (Reed et al. 2000, 2003; Nunes et al. 2004a; Reed and Minsker 2004; Wu et al. 2006; Kollat and Reed 2007; Kollat et al. 2008, 2011), minimisation of mass estimation error (Montas et al. 2000; Reed and Minsker 2004; Wu et al. 2005, 2006; Kollat and Reed 2007) etc. Masoumi and Kerachian (2010) applied an entropy theory for the redesign of optimal groundwater quality monitoring networks. Dhar and Datta (2009c) developed a number of different linear optimization formulations for groundwater monitoring using embedded Kriging. Sreekanth and Datta (2013) proposed a monitoring-network-design formulation which simultaneously considers placing a monitoring well where the prediction variance is maximum and also minimizes the co-variance of the concentration collected at monitored locations. Despite the large volume of work on optimizing monitoring network designs for groundwater systems, targeted works on compliance monitoring for coastal aquifers are largely absent.

Designing an optimal compliance-monitoring network would help monitor the aquifer system responses in real-time and enable intervention and modification of the groundwater management strategy if necessary. For instance, after operating an optimally designed pump-

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and-treat system, if the contaminant concentrations at a designated monitoring well is much higher than expected from the simulated values, it may be necessary to increase the pumping rates or add wells to ensure desired containment of the plume. Similarly, once an optimal pumping scheme for a coastal aquifer system to curb the landward movement of the saltwater has been in operation for a few years, but still indicates a rise in the concentration monitored at a compliance monitoring location, it may be necessary to re-evaluate and to alter the pumping rates and/or locations or prescribe a remediation strategy. Thus, the monitored data at the compliance monitoring locations provides feed-back information on the performance of the operating optimal groundwater management project based on which the current operation scheme could be continued or altered for operational or environmental benefit. Integrating the feedback information from the monitoring network in a real-time operation framework could improve the benefits accrued from the simulation-optimization. Cheng et al. (2011) illustrated a groundwater management model for real-time operation of an aquifer system where a nudging-data-assimilation algorithm was used to reduce the forecast error, minimize the risk of system error and improve management strategies. The nudging algorithm was used to estimate the missing pumping rates based on the head observations. Sreekanth and Datta (2013) illustrated how the information from the groundwater monitoring network is used as feedback information for modifying and updating the optimal groundwater management strategy using numerical model experiments. Monitoring feedback-based adaptive operation of coastal aquifers will be the key to the future real-time management of these heavily stressed aquifer systems. More theoretical and experimental studies in this direction are required to explore the opportunities for real-time, short-term and long-term coastal aquifer management.

Conclusion

Simulation-optimization is a valuable tool for developing regional-scale sustainable planning and operational design of groundwater management schemes for coastal aquifer systems. A wide range of groundwater flow and transport simulation models and optimization algorithms have been used for building simulation-optimization models. While the earlier optimization formulations were based on linear programming and classical non-linear optimization algorithms, a wide range of heuristic and evolutionary optimization techniques have been applied in the last two decades. Simulation models based on both sharp-interface and density-dependent dispersive-interface-modeling approaches have been used for simulation-optimization. Both these approaches have distinct advantages and disadvantages in the context of developing simulation-optimization models for coastal aquifer management.

Computational burden of simulation-optimization models is still a challenge for the application of simulation-optimization for coastal aquifer management problems. A large number of studies reported on the application of surrogate modeling techniques to reduce the computational burden of such models. Artificial neural networks (ANN) have been extensively used as a surrogate model, while modular neural networks, genetic programming and reduced order models have also been reported with specific advantages. Either a global training or adaptive training in offline or online modes may be carefully chosen on a case-by-case basis to yield maximum efficiency of the surrogate-model-based simulation-optimization application.

Increased research focus is required to develop simulation-optimization methodologies for coastal aquifer management incorporating model prediction uncertainty. Chance-constrained and multiple realization based methods employed in the wider groundwater management literature need to be adapted and tailored to develop reliable solutions for coastal aquifer management. Since the computational burden is the major challenge in incorporating prediction uncertainty in simulation-optimization, methods to do this with high computational efficiency also deserve special focus. Simulation-optimization approaches have also been widely used for designing optimal groundwater monitoring networks, while applications specific to coastal aquifer management are scarce. Some recent applications have explored the potential of real-time aquifer monitoring data in improving the management strategies. Improving the reliability of optimal solutions by accounting for the prediction uncertainty and incorporating the aquifer monitoring data to periodically optimize the management strategies may hold the key to beneficial implementation of the prescribed aquifer management strategies.

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