Coastal Aquifer Management Models: A Comprehensive Review on Model Development

Rajib K. Bhattacharjya and Triptimoni Borah

Abstract The demand for fresh water is accelerating as the world population is increasing in alarming rate. In order to cope with the increased demands, the overexploitation of groundwater resources has become unavoidable in many parts of the world. It has been reported that at least 70 % of the world population is living in coastal areas. The main sources of fresh water for these people are the freshwater aquifer near the coastal region. The unplanned exploitation of freshwater from coastal aquifers, hydraulically connected with sea or ocean may cause saltwater intrusion into coastal aquifers. The saltwater intrusion in coastal aquifers contaminates the aquifers and makes the coastal aquifers unusable for further human utilization. The contamination of coastal aquifers may also cause serious consequences on environment, ecology, and the economy of the region. The remediation of contaminated aquifers is generally very expensive and time-consuming. In order to protect the vital resource, it is necessary to protect coastal aquifers from further contamination by saltwater intrusion. Saltwater intrusion can be controlled by suitable management policies. The main objective of a coastal aquifer management model is to evolve planned operational strategies to meet required demand of fresh water while maintaining the salinity of water within permissible limit. In order to evolve a physically meaningful strategy, the flow and transport processes need to be simulated within the optimization-based management model. Different methodologies like embedded optimization method, response matrix approach, linked simulation optimization method, etc., have been developed to incorporate the aquifer simulation models with the management model. These methods have their own advantages and disadvantages and none of the methods can be declared as the best method for solving coastal aquifer management models. As such, a suitable method should be selected based on the data availability and other related local advantages. The study presents a review on development of coastal aquifer management models.

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1 Introduction

The demand for fresh water is accelerating as the world population is increasing in alarming rate. The overexploitation of groundwater resources has become unavoidable in many parts of the world. It is reported that at least 70 % of the world population live in coastal areas (Bear et al. 1999). The main sources of fresh water for those people are the freshwater aquifers near the coastal region. The unplanned exploitation of freshwater from coastal aquifers, hydraulically connected with sea or ocean may cause saltwater intrusion into coastal aquifers. The exploitation of coastal aquifers is restricted many times because of saltwater intrusion. The contamination of coastal aquifers in different parts of the world due to saltwater intrusion has been reported by many researchers. Rouve and Stoessinger (1980) reported degradation of groundwater reservoirs due to saltwater intrusion in the costal aquifer in Madras, India. Sherif et al. (1988) reported contamination of Nile delta aquifer in Egypt. Degradation of the costal aquifer in Yun Lin basin in southwestern Taiwan was reported by Willis and Finney (1988). Cheng and Chen (2001) also reported the degradation of the coastal aquifer in Jahi river basin, Shandong province in China due to saltwater intrusion. The main causes of saltwater intrusion into the coastal aquifers are mainly excessive exploitation of groundwater and improper arrangement of pumping wells. The problem of saltwater intrusion in the Middle East has been reported by Yakirevich et al. (1998) in Gaza Strip, Kacimov et al. (2009) in the coast of Oman, Shammas and Jacks (2007) in Salalah plain aquifer, Oman, etc.

Saltwater intrusion generally occurs, when excessive pumping from coastal aquifers lowers hydraulic potential. This allows seawater to move into the freshwater aquifers near coastal region. The saltwater intrusion in coastal aquifers contaminates the aquifers and makes the coastal aquifers unusable for further human utilization. The contamination of coastal aquifers may cause serious consequences on environment, ecology, and the economy of the region. The remediation of contaminated aquifers is generally very expensive and time-consuming. In order to protect a vital resource, it is necessary to protect coastal aquifers from further contamination by saltwater intrusion. Saltwater intrusion can be controlled by suitable management policies. The philosophy of coastal aquifer management policy is to maintain a balance between exploitation of coastal aquifers for withdrawing freshwater and restricting the movement of saltwater in coastal aquifers. Therefore, the main objective of a coastal aquifer management model is to evolve planned operational strategies to meet required demand of fresh water, while maintaining the salinity of water within permissible limits. In order to evolve a physically meaningful strategy, the flow and transport processes need to be simulated within the optimization-based management model. This would ensure that the prescribed optimal strategies obtained as solutions of the management model would accurately represent the response of the aquifer. In this paper, an attempt has been made to discuss the various issues related to the development of the saltwater intrusion management model. The issues discussed here are: saltwater intrusion process in a coastal aquifer, simulation of saltwater intrusion process in a coastal aquifer, incorporation of simulation model with optimization-based management model, optimization algorithms, and coastal aquifer management model.

1.1 Saltwater Intrusion Process in Coastal Aquifer

Saltwater intrusion is generally caused by unplanned exploitation of freshwater from coastal aquifers. The heavier salt water has the tendency to underlie freshwater because of the hydrodynamic mechanism. At the same time, a mixing zone of varying density also exists between freshwater and saltwater due to hydrodynamic dispersion. This zone is known as the transition zone or, the zone of dispersion or diffusion. In this zone, the density of the mixed fluid increases gradually from freshwater to saltwater. Figure 1 shows the vertical section of an unconfined coastal aquifer with the transition zone. The thickness of the transition zone may vary from few meters to more than hundred meters (Todd 1980). The transition zone may be ignored during the development of simulation model when the thickness of the zone is relatively small. In this case, salt water and fresh water may be considered as immiscible fluid and the interface would be a sharp interface. Figure 2 shows the vertical section of an unconfined coastal aquifer with a sharp interface between saltwater and freshwater. The sharp interface does not provide any information about the nature of the zone of dispersion. For a large thickness of the transition zone, sharp interface model may give an erroneous result. Also, the sharp interface modeling approach may not be adequate when the mixing zone is large, and saline concentrations in between freshwater and saline water cannot be incorporated into the management model. Therefore, for real world saltwater intrusion problem, the

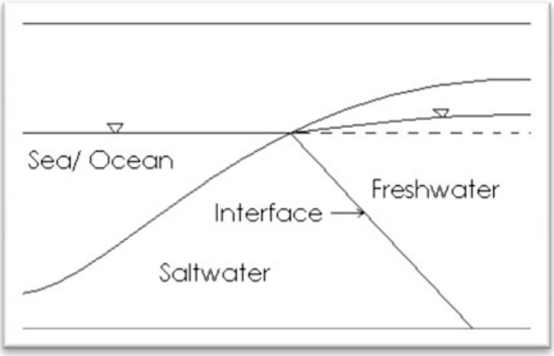

Fig. 1 Vertical cross section of an unconfined coastal aquifer (without transition zone)

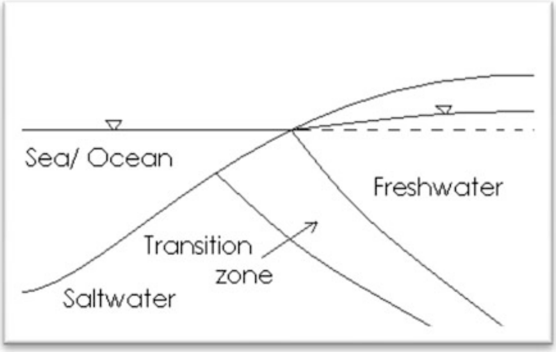

Fig. 2 Vertical cross section of an unconfined coastal aquifer (with transition zone)

transition zone needs to be considered for simulating saltwater intrusion process in coastal aquifers. Incorporation of the transition zone makes the simulation of saltwater intrusion process highly complex. In this case, both flow and transport processes become density dependent.

1.2 Simulation of Saltwater Intrusion Process

Saltwater intrusion is caused by overexploitation of groundwater from coastal aquifers. The higher density saltwater generally stays separate from low-density fresh water. However, as discussed above a mixing zone exists because of hydrodynamic dispersion. The mixing zone is also known as transition zone or zone of diffusion or dispersion. For narrow transition zone, the interface may be assumed as a sharp interface (Fig. 2). In this case, the effect of hydrodynamic dispersion is considered as negligible. Analytical solutions of sharp interface model for single homogeneous aquifers have been reported by Henry (1959), Bear and Dagan (1964), Dagan and Bear (1968), Hantush (1968), Schmorak and Mercado (1969), and Strack (1976). Analytical solutions for layered aquifers were also presented by Mualem and Bear (1974), and Collins and Gelhar (1971). All of these researchers applied Dupuit approximation to obtain analytical solutions. Numerical simulations of sharp interface model were presented by Mercer et al. (1980), Polo and Remis (1983), Taigbenu et al. (1984), Essaid (1990), Huyakorn et al. (1996), Guvanasen et al. (2000), etc.

Moreover, sharp interface approximation does not give any idea about the transition zone. This sharp interface approach is not applicable when permissible limits on saline concentration are imposed on management strategies so that some portion of the transition zone satisfies these restrictions. As such for simulating the real-world scenarios, the transition zone has to be considered during the development of the simulation model. In this case, the flow and transport equations are coupled together by density coupling term. As a result, of this coupling, the simulation of the process becomes complex and time-consuming. Henry (1959) presented the first analytical solution considering transport of salt in density-dependent fluid flow condition for steady state condition in a confined coastal aquifer. The numerical solution of the Henry's problem was presented by Pinder and Cooper (1970) for transient condition using the method of characteristics. Lee and Cheng (1974) presented the first finite element-based simulation model to solve saltwater intrusion problem in coastal aquifers. They adopted elliptical type governing equations. They used stream function and considered salt concentration as dependent variables. Galerkin finite element technique was used by Segol et al. (1975) to solve saltwater intrusion problem dominated by advective transport. Huyakorn and Taylore (1976) presented a model using reference hydraulic head and concentration as dependent variables. The simulation of saltwater intrusion process for an aquifer–aquitard system was presented by Kawatani (1980) and Frind (1982) using Galerkin finite element technique. Volker and Rushton (1982) used finite difference technique, and Rubin (1983) used boundary layer approximation technique to simulate saltwater intrusion process in coastal aquifers. Voss (1984) developed finite element-based SUTRA code for simulation of density depended on saltwater intrusion process in two-dimensional coastal aquifers. Till date, SUTRA has been considered as one of the best simulation models and has been used by many researchers to solve the density-dependent saltwater intrusion process in a coastal aquifer. Some other significant contributions in simulation of saltwater intrusion process are Sherif et al. (1988), Galeati et al. (1992), Cheng et al. (1998), Tejeda et al. (2003), Huyakorn et al. (1987), Putti and Paniconi (1995), Das and Datta (2000), Cheng and Chen (2001), etc.

1.3 Incorporation of Simulation Model with Optimization Model

In order to obtain physically meaningful management strategies, the coastal aquifer simulation model has to be incorporated into the management model. Embedding technique and response matrix approach (Gorelick 1983) are the two methods generally used to incorporate governing equations within the management model. The embedded optimization technique incorporates finite difference or finite element approximation of the governing equations as equality constraints within the management model, along with the other physical and managerial constraints. Incorporation of the highly nonlinear flow and transport equations within the optimization model as equality constraints convert the optimization problem into a non-convex nonlinear problem. The solution of such non-convex nonlinear optimization problem is difficult as there are several local optimal solutions. The applicability of embedding technique for saltwater intrusion problem (Das 1995; Das and Datta 1999a, b) is limited, especially for large-scale aquifer systems. This approach is also numerically inefficient, especially when applied to large aquifer systems with considerable heterogeneity. The response matrix approach is based on the principle of superposition and linearity. In this case, an external simulation model is used to generate the response matrix. This method is reported to be unsatisfactory for highly nonlinear systems (Rosenwald and Green 1974) such as density-dependent saltwater intrusion in coastal aquifers.

As an alternative to the embedding technique and the response matrix approach, the numerical simulation model may also be incorporated into the management model as an external module. In this approach, an external simulation model is linked to the optimization model (Finney et al. 1992; Emch and Yeh 1998). The optimization model calls the simulation model as and when it requires any information from the simulation model. The methodology has been applied effectively for solving large-scale groundwater management models (Bhattacharjya and Dutta 2009). The main disadvantage of this approach is that numerous repetitive iterations between the simulation model and the optimizer are required to arrive at an optimal solution. As the simulation of flow and transport processes are highly nonlinear and time-consuming in the case of coastal aquifers, this linked simulation optimization approach would take a considerable computational time to obtain the optimal solution. The computational time can be substantially reduced by utilizing parallel processing capabilities of advanced computers. This would enable the use of rigorous numerical models for simulations and its linkage to an optimization model. Also, the time requirement for iterative solutions of the optimization model and the simulation model can be drastically reduced. However, this requires appropriate computer hardware and numerical simulation models specially tailored to explicit parallel processing capabilities. Another alternative for reduction of computational time is the use of an approximate simulation model in place of the actual numerical simulation model. The approximate simulator is generally less costly in terms of computational time and computer hardware requirements. Regression analysis and artificial neural networks (ANN) model are generally used for approximating the flow and transport processes in groundwater. The ANN model is considered as a better approximator than regression analysis since it can handle partial information. Also, the performance of the approximate simulation model does not degrade much with noisy data (Bhattacharjya et al. 2007). Applications of regression analysis for approximating an aquifer processes within a management model are reported by Alley (1986), and Lofkoff and Gorelick (1990). Applications of ANN model for approximate simulation of aquifer processes are reported in Rogers and Dowla (1994), Morshed and Kaluarachchi (2000), Aly and Parelta (1999b), Johnson and Rogers (2000), Bhattacharjya et al. (2007), etc. It may also be mentioned here that the Genetic Programming can also be applied to develop an approximate coastal aquifer simulation model. Incorporation of these approximate simulation models would drastically reduce the computational time of the management model. However, care has to be taken in evaluating the performance of the approximate simulation model.

2 Optimization Algorithms

An optimization algorithm is required for solving the aquifer management models. Classical optimization techniques, e.g., linear programming, nonlinear programming, mixed integer programming were used extensively for solving saltwater intrusion management problems (Shamir et al. 1984; Willis and Finney 1988; Finney et al. 1992; Hallaji and Yazicigil 1996, Emch and Yeh 1998; Loaiciga and Leipnik 2000; Das and Datta 1999a, b, etc.). The main disadvantage with most of the classical methods is their dependence on gradient search technique. Most of the time, these gradients are calculated numerically. The numerical estimation of gradients is often the most time-consuming part of an optimization problem. Moreover, numerical calculation of gradients sometimes may lead to severe errors. Another disadvantage of classical optimization techniques is that many times it is inefficient in avoiding local optimal solutions, especially when the optimization problem is a non-convex one and response surface is highly irregular. One possible remedy is the use of multiple solution points as an initial solution. The other limitations of classical methods are point-to-point search, the necessity of initial guesses, deterministic transition rule, the assumption of unimodality, etc. (Deb 2001). It may be noted that classical optimization techniques are not efficient to solve multiple objectives coastal aquifer problems. The classical optimization techniques require several runs to obtain the Pareto-optimal solutions of a multiobjective optimization problem. As such, some researchers have used non-classical optimization techniques, such as Genetic Algorithm for solving coastal aquifer management models. Genetic Algorithms is a search technique based on the concept of natural selection inherent from natural genetics. It is relatively more efficient in obtaining the global optimal solution even when the response surface is highly irregular. GA is also efficient in handling multiple objectives optimization problems, as it can generate the entire nondominating front (Pareto-optimal solutions) in a single run. Another advantage of GA is the relative ease in solving an externally linked simulation optimization model. Due to the various advantages over classical optimization methods, genetic algorithm has been used efficiently for solving various groundwater management models (Ritzel et al. 1994; Mckinney and Lin 1994; Rogers and Dowla 1994; Cieniawski et al. 1995; Aly and Peralta 1999a, b; Morshed and Kaluarachchi 2000; Bhattacharjya and Dutta 2009, etc.).

3 Coastal Aquifer Management Models

The coastal aquifers management models are generally formulated to achieve specific objectives, such as maximum exploitation to cope with the increasing demands, in a best possible way without causing salt intrusion into the aquifers. The management models may have various managerial and physical limitations. These managerial and physical restrictions are incorporated within the management models as constraints. Development of management models has been reported by many researchers. Most of the models reported earlier used sharp interface approximation of the interface between saltwater and freshwater. Shamir et al. (1984) presented a linear programming model to determine the optimal annual operation of a coastal aquifer. Willis and Finney (1988) also adopted sharp interface approximation of transition zone for optimal control of saltwater intrusion in Yun Lin aquifer in Taiwan. They used finite difference approximation of the governing equations to simulate the response of the aquifer to management strategies. The developed models were solved by influence coefficient method allied with quadratic programming technique, and reduce-gradient methods in conjunction with a quasi-Newton algorithm. Finney et al. (1992) presented a quasi three-dimensional optimization model for control of saltwater intrusion in Jakarta multiple aquifer system. They used finite difference approximation to generate hydraulic-response equations of the groundwater basin by relating freshwater and saltwater heads, the location of the interface, and the pumping and recharge schedules. They considered saltwater and freshwater interface as sharp as the zone of diffusion was relatively narrow. They solved their optimization model using MINOS. Hallaji and Yazicigil (1996) presented groundwater management model to determine optimal planning and operational policies of a coastal aquifer in southern Turkey. They used response matrix approach and the finite-element-based flow and transport simulation model SUTRA to generate the response matrix. They considered three management objectives. Those were the maximization of agricultural water withdrawals, minimization of drawdown, and minimization of pumping cost. They presented their results in the form of tradeoff curves relating optimal pumping rates and pumping costs. Emch and Yeh (1998) presented nonlinear multiple objectives management model for management of water used within coastal aquifers. They used linked simulation optimization technique similar to Finney et al. (1992). They assumed sharp interface approximation of the transition zone. They linked the quasi three-dimensional finite-difference-based groundwater flow model SHARP (Essaid 1990) with the optimization model. SHARP simulates both saltwater and freshwater dynamics for layered aquifer for steady and transient conditions. The optimization model was solved using MINOS. The two conflicting objectives considered in their study were cost-effective allocation of surface and groundwater supplies and minimization of saltwater intrusion. They adopted constraint method to convert the multiobjectives optimization model to a single objective optimal management model. Loaiciga and Leipnik (2000) derived closed form solutions of a groundwater management model for coastal aquifers. The objective of the model was the maximization of long-term revenue subjected to climatic, hydrologic, and environmental constraints. The proposed model is applicable to relatively homogeneous aquifer systems and limited size. The climatic and environmental conditions were assumed as uniform. Cheng et al. (2000) presented an optimization model to optimize pumping from saltwater-intruded coastal aquifers for steady state condition. They have considered sharp interface aquifer simulation model by considering saltwater and freshwater as immiscible fluid. They employed Dupuit assumptions to convert three-dimensional problem to a two-dimensional problem. They presented an analytical solution for one well, two wells, and one well with recharge canal problems. For the problem with multiple wells, a structured messy Genetic Algorithm was used to search for an optimal solution.

The sharp interface approximation of saltwater and freshwater interface is not acceptable especially when the thickness of the transition zone is large. Moreover, sharp interface approximation does not give any idea about the transition zone. The sharp interface approach is not applicable when permissible limits on saline concentration are imposed on management strategies so that some portion of the transition zone satisfies these restrictions. Das and Datta 1999a, b) presented a number of nonlinear optimization-based multiple objectives management models for sustainable utilization of coastal aquifers. The objectives considered by them were the maximization of total pumping from the coastal aquifer, minimization of maximum salt concentration in the monitoring wells and minimization of barrier pumping. It may be noted that barriers pumping is a very effective measure to control seawater intrusion. In this method, a hydraulic barrier is constructed artificially to restrict the intrusion of saltwater into the inland side of the aquifer. Das and Datta 1999a, b) used the embedded optimization technique. The nonlinear finite difference approximation of density-dependent miscible flow and transport equations were added as embedded constraints to the management models. They have reported the difficulties of the embedded approach especially for large-scale real-world coastal aquifer problem and also reported the necessity of large computational time. In order to reduce the computational time of the simulation optimization model, Bhattacharjya and Datta (2009) presented linked simulation optimization model using ANN and GA for deriving multiple objectives management strategies for coastal aquifers. They have approximated the three-dimensional simulation model using ANN and the ANN model is then linked with the GA-based coastal aquifer management model. In this process, they have shown that the computational time of the simulation optimization model can be reduced drastically. They have solved different single and multiple objectives optimization problems for demonstrating the efficiency of the developed methodology. Sreekant and Datta (2011) applied Genetic programming to approximate the saltwater intrusion process.

4 Conclusions

A review on development of saltwater intrusion management models in a coastal aquifer is presented. The development of saltwater intrusion simulation models, coastal aquifer management models, and multi-objective coastal aquifer management models are discussed. The use of approximate simulation model in developing coastal aquifer management model is also reviewed. It is hoped that the discussed made here will be useful for the new research to develop coastal aquifer management model.

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