Multi-objective management models for optimal and sustainable use of coastal aquifers

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Extended Abstract

INTRODUCTION

Land areas adjacent to the world's shorelines support large and ever-increasing concentration of human population, settlements and socio-economic activities, including many of the world's large cities. It has been estimated that more than half of the world's population lives within 60 km from the shore line (UNCED, 1992). Evidently, conservation and sustainable use of the water resources of these areas assume great importance. Coastal aquifers, i.e., aquifers which are hydraulically connected to the sea, are a major source of freshwater in such areas. Due to the hydraulic continuity with the sea, coastal aquifers are susceptible to salinity intrusion caused by a number of factors, the major ones being the unplanned over-exploitation of the groundwater resource and sea level rise due to climate change. Saltwater intrusion occurs in coastal and deltaic regions all over the world, where the population density is high and many human activities take place. Saltwater intrusion in coastal aquifers can prevent the beneficial use of aquifers due to the increased salinity of the groundwater thereby causing great economic and environmental loss to the society. Sustainable use of coastal aquifers requires design and implementation of sustainable management strategies. This study is aimed at developing optimal and sustainable management policies for coastal aquifers.

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

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

One of the main reasons behind saltwater intrusion is the overexploitation of the coastal aquifers which disrupts the saltwater-freshwater balance. Hence the most direct and economical management alternative is to carefully plan and monitor the withdrawal strategies from the coastal aquifer. To study the effects of different withdrawal strategies on the aquifer salinity the aquifer system needs to be reliably simulated. Numerical simulation models could be used to evaluate the different management alternatives for its effect on the aquifer system. Optimal management strategy cannot be identified by sequentially using the simulation models as there is infinite number of alternative withdrawal strategies possible. Optimization models are used in a linked simulation-optimization framework to identify the optimal withdrawal strategy for coastal aquifers. In the linked simulation-optimization, each iteration of the optimization model calls the simulation model which provides the necessary information to the optimization model. As each simulation model takes considerable time to execute, the CPU time required for the linked simulation-optimization is very large. In order to reduce this, trained and tested surrogate models like neural networks are used to replace the numerical simulation model within the optimization model. This permits incorporation of any complex simulation model within the optimization search.

A few studies have used density dependent flow and transport models for developing management models (Das and Datta, 1999; Qahman, 2005). Dhar and Datta (2009) used the density dependent flow and transport simulation model FEMWATER for developing a multi-objective management model. Some studies have used surrogate models to replace the actual numerical simulation model to reduce the computational complexity. The earliest form of surrogate model is the response matrix approach. Response matrices are simplified linear approach to simulate the aquifer responses. Response matrix approach have been used by Hallaji and Yazicigil (1996), Zhou et al. (2003), Abarca et al. (2006) etc. Complex surrogate models like Artificial Neural Networks have been used more recently due to its capability to model highly non-linear functions. Neural network based surrogate models for salinity intrusion management were developed by Bhattacharya and Datta (2005), Rao et al., (2004) and Dhar and Datta (2009).

In this work we develop a surrogate based linked simulation-optimization methodology for the multi-objective optimal management of coastal aquifers. A genetic programming based surrogate model for simulating the aquifer processes is linked to a multi-objective genetic algorithm to develop the management model.

METHODOLOGY

In a linked simulation optimization approach each iteration of the optimization algorithm calls the simulation model for constraint evaluation. A three dimensional density-dependent flow and transport simulation model FEMWATER (Lin *et al*., 1997) is chosen to simulate the coupled flow and transport process. Depending on the complexity of the problem the optimization algorithm may have thousands of iterations before converging to an optimal solution. With the 3D density dependent simulation model itself taking considerable time for a single run, the computational burden on the linked simulation optimization model is huge. The computational burden is reduced by using properly trained and tested surrogate models to replace the actual numerical simulation model. With sufficient training, a neural network model or genetic programming model is able to mimic the complex numerical simulation model with acceptable accuracy levels. While the run time of an FEMWATER takes a few minutes to a couple of hours, depending on the model size and complexity, a properly trained surrogate model can generate the required results in a fraction of a second.

In this study we use genetic programming based surrogate model for simulating the aquifer responses to pumping for a small coastal aquifer system. The genetic programming (GP) based surrogate model is trained and tested using the aquifer response to pumping data obtained from FEMWATER model. Properly trained and tested GP models are computationally linked to a multi-objective genetic algorithm. The multi-objective genetic algorithm (Deb, 2001) solves the optimization problem of determining the optimal pumping strategies for the coastal aquifer system so that the resulting salinity intrusion into the aquifer is controlled to be within pre-specified maximum limits.

Saltwater intrusion can be hydraulically controlled on regional scale by planned withdrawal of water in space and time. Also, planned pumping from a set of barrier wells situated along the coastline. These two management methods are considered as two objectives in the present study.The first objective of management is maximization of total pumping from the production wells extracting groundwater from the aquifer. The second objective is to minimize the total pumping from the barrier wells near the coast which pumps out saline water to hydraulically control saltwater intrusion. Eight pumping well locations and three barrier well locations were considered. The salinity levels were monitored at three monitoring locations, viz, C1, C2 and C3.

The mathematical formulation of the optimization problem is given as follows;

$$Maximize, f_1(Q) = \sum_{n=1}^{N}\sum_{t=1}^{T} Q_n^t \qquad (1)$$

$$Minimize, f_2(Q) = \sum_{m=1}^{M}\sum_{t=1}^{T} q_m^t \qquad (2)$$

s.t. $c_i = \xi(Q,q)$ (3)

$c_i \le c_{\max} \forall i,t$ (4)

$Q_{\min} \le Q_n^t \le Q_{\max}$ (5)

$q_{\min} \le q_m^t \le q_{\max}$ (6)

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. $\xi(\ )$ represents the density dependent flow and transport simulation model and constraint (3) represents the coupling of the simulation model with the optimization model. M, N and T are respectively the total number of production wells, total number of barrier wells and total number of time steps in the management model. Constraint (4) imposes the maximum permissible salt concentration in the monitoring well locations. Constraints (5) and (6) define lower and upper bounds of the pumping from production wells and barrier wells respectively.

RESULTS AND DISCUSSION

A surrogate model based linked simulation-optimization methodology was developed for the management of a small coastal aquifer system. The model is capable of handling multiple objectives of optimization. A multi-objective optimization problem has a non-dominated front of optimal solutions which has a trade-off between the conflicting objectives. The non-dominated front of solutions obtained for the coastal aquifer management problem considered in this study is shown in Fig 1. On the front it can be observed that for any improvement in one objective function value requires a corresponding decline in the second objective function value. Five solutions on the front were validated for the prediction accuracy of the surrogate model by comparing the salinity predictions at C1, C2 and C3 with actual numerical simulation model predictions. The comparison is shown in table 1.

Table 1. Validation of the surrogate model predictions for the optimal solutions

Solution	$C1 \leq 0.5$ kg/m^3		$C2 \leq 0.6$ kg/m^3		$C3 \leq 0.6$ kg/m^3	
	GP 10^{-3} kg/m^3	Numerical model 10^{-3} kg/m^3	GP 10^{-3} kg/m^3	Numerical model 10^{-3} kg/m^3	GP 10^{-3} kg/m^3	Numerical model 10^{-3} kg/m^3
1	500.0	500.6	571.8	572.3	599.5	604.2
2	500.0	502.2	573.6	571.2	599.0	595.6
3	500.0	501.1	562.4	563.1	599.7	598.7
4	500.0	497.6	558.1	557.3	599.5	598.5
5	500.0	500.5	558.0	554.8	599.5	598.8

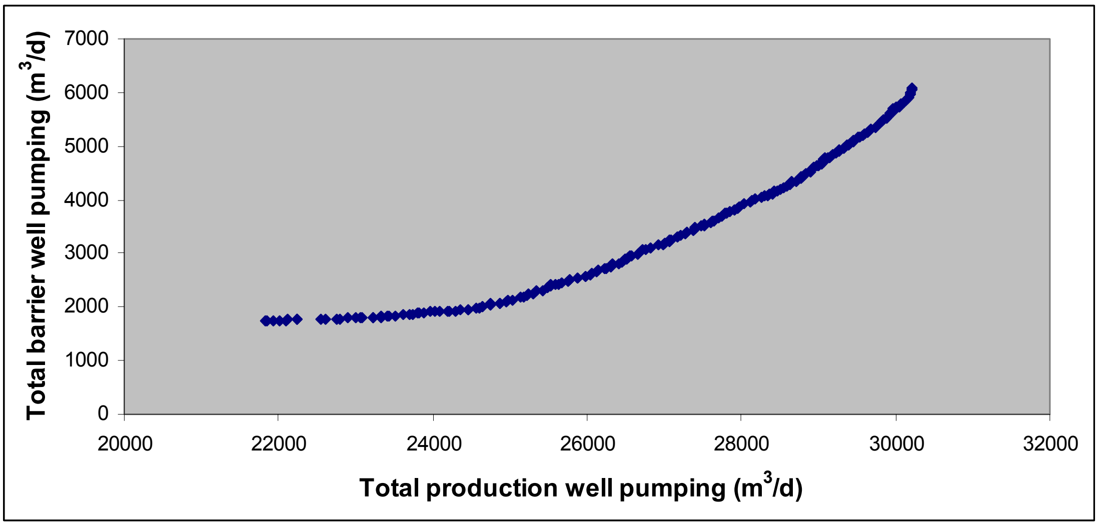

Fig 1. Non-dominated front of solutions for the coastal aquifer management problem

CONCLUSIONS

A management model for the optimal management of coastal aquifers is developed using surrogate based simulation and multi-objective genetic algorithm. The multi-objective optimization algorithm is able to derive the entire non-dominated front of solutions to the management problem in one single run of the optimization model. The linked simulation optimization models have potential applicability in the solving a wide range of regional groundwater management problems like optimal remediation design, management of coastal aquifers and wetlands, optimal pump and treat designs, optimal monitoring network design etc.

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