Numerical modelling and control of seawater intrusion in coastal aquifers

Modélisation numérique et contrôle des intrusions d'eau de mer dans les aquifères côtiers

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ABSTRACT: This paper presents the results of an investigation into numerical modelling and control of seawater intrusion. A coupled transient density-dependent finite element model has been used for modelling of seawater intrusion. Also, a new cost-effective method is presented for effective control of seawater intrusion in coastal aquifers. This methodology ADR (Abstraction, Desalination and Recharge) includes abstraction of saline water, desalination and recharge of a part of the excess desalinated water to the aquifer while the rest of the desalinated water can be used for domestic consumption. The simulation model has been integrated with an genetic algorithm (GA) to examine different scenarios to control seawater intrusion including different combinations of abstraction, desalination and recharge. The main objectives of the model are to minimize the total capital and operational costs of the abstraction and recharge wells and the salt concentrations in the aquifer. The results show that the proposed ADR system performs significantly better than using abstraction or recharge wells alone as it gives the least cost and least salinity in the aquifer.

RÉSUMÉ : Cet article présente les résultats d'une étude sur la modélisation numérique et le contrôle des intrusions d'eau de mer. Un couplage transitoire à densité variable par éléments finis a été utilisé pour modéliser les intrusions d'eau de mer. De plus, une nouvelle méthode est présentée pour un contrôle optimisé des intrusions d'eau salée. Cette méthodologie ADR (Abstraction, Desalination and Recharge) inclut l'extraction d'eau saline, le dessalement et la recharge dans l'aquifère d'une partie de l'excès d'eau dessalée tandis que le reste d'eau dessalée peut être utilisée pour un usage domestique. Le modèle de simulation a été intégré à l'aide d'un algorithme génétique (GA) dans le but d'examiner différents scénarios pour le contrôle des intrusions d'eau de mer incluant différentes combinaisons d'extraction, de dessalement, et de recharge. L'objectif principal du modèle est de minimiser le coût total et le nombre d'opérations pour l'extraction et la recharge des puits ainsi que la concentration en sel dans l'aquifère. Les résultats montrent que la méthode ADR proposée donne de biens meilleurs résultats que l'extraction et la recharge des puits seules du fait qu'elle conduit à un coût et une salinité dans l'aquifère minimaux.

KEYWORDS: numerical modelling, seawater intrusion, optimal management, abstraction, recharge

1 INTRODUCTION.

Seawater intrusion is a major problem threatening water resources in many parts of the world. The intrusion of saline water in groundwater is considered a special category of pollution, making groundwater resources unsuitable for human, industrial and irrigation uses. Mixing of 2-3% salinity would render the fresh groundwater resources unsuitable for human consumption. A 5% mixing of salinity with freshwater in an aquifer is enough to make the aquifer unsuitable for any use (Abd-Elhamid and Javadi, 2011). Seawater intrusion hence reduces the freshwater storage in coastal aquifers and in extreme cases can result in abandonment of freshwater supply wells. Remediation of groundwater could be very costly and could take a long time depending on the source and level of salinization. As a result, groundwater resources should be protected from saltwater intrusion, using suitable measures. To control saline intrusion, a seaward hydraulic gradient should be maintained and a proportion of the fresh-water should be allowed to flow into the sea. Risks of saline intrusion clearly limit the extent to which a coastal aquifer can be developed for water supply. The management of a coastal aquifer is concerned with deciding an acceptable ultimate landward extent of the saline water and calculating the appropriate discharge of freshwater necessary to maintain the seawater-fresh water interface in that position. A number of methods have been proposed to control seawater intrusion including: reduction of pumping rates, relocation of pumping wells, use of subsurface barriers, natural recharge, artificial recharge, abstraction of saline water and combination techniques (Todd, 1974). This study presents a cost-effective methodology to control seawater intrusion in coastal aquifers. This methodology (ADR - Abstraction, Desalination and Recharge) consists of three steps; abstraction of brackish water from the saline zone, desalination of the abstracted brackish water using reverse osmosis (RO) treatment process and recharge of the treated water into the aquifer.

Generally, the seawater intrusion is a highly nonlinear process. Spatial and temporal simulation of this process will require numerical methods such as the finite element method or finite difference method to solve the nonlinear governing equations of flow and solute transport through saturated/unsaturated porous media. Numerical simulation models can be used to examine a limited number of design options of these management methods, by trial and error (e.g. Mahesha, 1996 and Rastogi et al., 2004). However, optimization tools can be combined with simulation models to search for the optimal solution in a wide search space of design variables.

In recent years, a number of simulation models have been combined with optimization techniques to address groundwater management problems. The combined simulation and optimization model can identify an optimal management strategy by considering appropriate management objectives and constraints. The genetic algorithm (GA) optimization tool has the capability to deal with a wide range of optimization problems. These techniques have been applied by a number of researchers to coastal aquifer problems. Different simulation

management model is the most cost effective strategy to control the seawater intrusion in this hypothetical aquifer. The cost of this model is about 50% of the abstraction only scenario and 25% of the recharge scenario. The reason for this lowest cost is partly because the cost associated with the supply of water used for recharge does not apply in this case as the required water is provided primarily from the treatment of the abstracted saline water. In addition, the excess treated water can be directly used for other purposes. The other aspect of efficiency of this model is about minimization of total concentration of salinity in the aquifer as it reduced the total concentration in the system by 15% , while the first and second scenarios reduced it by 10-11%. Figure (4) clearly shows the capability of third model in controlling the further advance of the freshwater/seawater interface in comparison with other models.

Table 2. Summary of the results obtained from the simulation-optimization models for the hypothetical case study.

Model	L (m)	D (m)	Q (m^3/sec)	Total C	Cost ($/year)
No Management	-	-	-	167	-
Abstraction only	50	90	-0.083	149	2.62E+6
Recharge only	90	60	0.095	151	5.72E+6
Abstraction and Recharge	50 110	90 80	-0.048 0.018	142	1.32E+6

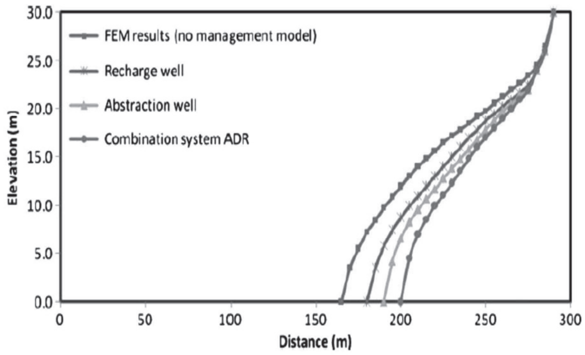

Figure 4. 0.5 isochlors from simulation-optimization models for the hypothetical case.

6 CONCLUSIONS

This paper presented the development and application of a simulation-optimization model to control seawater intrusion in coastal aquifers. A coupled transient density-dependent finite element model was used to simulate the seawater intrusion problem. This simulation model was linked with a genetic algorithm to optimize control arrangements for a hypothetical aquifer using three management scenarios: abstraction of brackish water, recharge of fresh water, and combination of abstraction and recharge. The efficiencies of the proposed management scenarios in controlling seawater intrusion in terms of both the solute concentration in the aquifer and the total costs (of construction and operation) of the management policy were evaluated using this integrated model. The optimal locations, depths, and rates of abstraction and/or recharge wells in each scenario were determined. The results show that all three scenarios could be effective in controlling sea intrusion but using model 3 (a combination of abstraction and recharge wells) resulted in the least cost and salt concentration in aquifers and maximum movement of freshwater/saline water interface towards the sea. The results also show that for the case study considered in this paper, the amount of abstracted and treated water is three times the amount required for recharge; therefore, the remaining treated water can be used directly for different purposes. Finally, ADR is an effective tool to control seawater intrusion and can be applied in areas where there is a risk of seawater intrusion.

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