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Artificial Injection to Control Saltwater Intrusion in Groundwater-Numerical Study on a Vertical Cross Section

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지하수 해수쐐기 제어를 위한 인공주입-연직 2차원 단면 수치실험

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A simulation-optimization model is developed for development of groundwater and control of a saltwater wedge for protecting over-exploiting freshwater pumping wells. To achieve the goal an objective function is developed for three types of wells: freshwater pumping, freshwater injection and saltwater pumping. Integrity of groundwater environment is accounted for by including three indices. Illustrative cross-sectional examples show that both types of barriers can protect freshwater pumping wells from saltwater intrusion. A barrier well operating at the same rate located anywhere within a certain reach can protect a pumping well. However, the location of the reach appears to contradict the common practice of barrier placements. Consideration of the groundwater environment yields a unique optimal location for barrier wells.

Key words : saltwater intrusion, injection barriers, simulation-optimization, protection of over-exploiting wells

해안지역에서 과잉 양수정 보호를 위한 최적 해수쐐기 제어 전산모델을 개발하였다. 최적화 목적함수는 세 가지 종류의 관정에 대하여 유도되었다: 담수 양수, 담수 주입 그리고 해수 양수. 지하수 개발과 쐐기 제어로 인하여 지하수 체에 미치는 영향을 고려하기 위하여 환경인자를 도입하였다. 가상 연직단면에 대한 적용 예에서 담수 인공 주입을 통하여 해수침투로부터 과잉 양수정을 보호할 수 있음을 보였다. 연직 단면 수치실험에서는 주입량 조건이 만족되면 여러 주입 위치에서 동일하게 과잉 양수정을 보호할 수 있는 것으로 나타났다. 그러나 지하수 환경인자를 고려하면 최적 주입위치가 고유하게 결정된다.

주요어 : 해수침투, 주입정, 모의-최적화, 과잉 양수정의 보호

Introduction

One of the most important issues regarding groundwater resources in coastal areas is saltwater intrusion. Numerous studies were conducted to assess optimal freshwater pumping rates of groundwater subject to potential saltwater intrusion. Analytical solutions (Cheng and Ouazar, 1999; Strack, 1976) based on stagnant saltwater and the sharp interface approximation have been often used in optimization. Park and Aral (2004) presented an enhanced model that can identify optimal well locations as additional decision variables.

Hydraulic means to either hinder or prevent an advancing saltwater wedge include injection and extraction barriers. Injecting freshwater forms a hydraulic barrier that raises freshwater piezometric head. Many investigations were conducted to study performances of injection barriers (Bruington, 1968;

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Nellor et al., 1990; Rose, 1990; Schroeder et al., 1989). Johnson and Whitaker (2002) studied alternatives citing the high cost of injection barriers. Injection barriers were used elsewhere in Florida and in Long Island, New York.

Relatively a few studies were conducted on optimal control of an interface. Reichard and Johnson (2005) used a response function generated from a freshwater flow model to determine optimal injection rates. However, use of the three-dimensional density-dependent model in an optimization problem makes the computational burden too high even for advanced computers available today. The proposed model is composed of a simulation model and an optimization routine. This paper focuses on the construction of the objective function and illustrative examples by which effectiveness of freshwater injection and saltwater pumping is investigated.

The model can identify freshwater pumping rates and well locations for optimal groundwater development. In addition the model can also identify optimal injection/extraction rates and locations to protect freshwater pumping wells. Impacts on groundwater environments induced by various types of wells can also be considered. A sharp-interface numerical model is used for simulating flows of freshwater and saltwater (Huyakorn et al., 1996). Therefore, the model is not subject to usual limitations associated with analytical solutions. Ability to model saltwater flow is essential in design of an extraction barrier. The sharp interface model is less rigorous in treating physics than a density-dependent model, but has significant advantages in computational demand. For optimization, a genetic algorithm is used which guarantees near global optimal solutions.

The model is applied to a hypothetical cross section to investigate performances of injection barriers not only for control of saltwater wedge but also for protection of freshwater pumping wells. Optimal injection rates and locations are studied with and without considering impacts on groundwater environment. This study attempts to answer using an optimization model in the context of examples of a cross sectional aquifer.

Optimization Model

For optimal groundwater development and saltwater-freshwater interface control the model must be able to deal with three types of wells: freshwater (FW) pumping wells, freshwater injection wells, and saltwater (SW) pumping wells. For this study the following aspects are considered in constructing the objective function. For benefits:

- freshwater pumping rates
- positive impact on groundwater environment

For costs and penalties:

- cost of freshwater injection
- cost of saltwater pumping
- penalty for saltwater production from freshwater pumping wells
- penalty for freshwater production from saltwater pumping wells
- adverse impacts of pumping on groundwater environment

Well locations and operation rates are primary design parameter.

Combined objective function

Freshwater withdrawal and positive impacts on groundwater system are considered benefits, that need to be maxized.

Maximize

$$\chi_x^2=\sum_{k=1}^{N_{pfo}} Q_{pf,k}+\left(\sum_{k=1}^{N_{pfo}} Q_{pf,k}+\omega_i\sum_{k=1}^{N_{ifo}} Q_{if,k}+\omega_c\sum_{k=1}^{N_c} Q_{c,k}\right)w_\alpha\alpha \qquad (1)$$

where N_{pfo} is the number of freshwater pumping wells that are subject to optimization; one term is missing but exits in the hangul file is the freshwater production rate (> 0) from the k^{th} freshwater pumping well; N_{ifo} is the number of injection wells for which injection rates and/or locations are to be optimized; $Q_{if,k}$ is the freshwater injection rate (<0) from the k^{th} freshwater injection well; N_c is the number of saltwater pumping wells; $Q_{c,k}$ is the saltwater pumping rate (> 0) from the k^{th} scavenger well; ω_i and ω_c

are weights representing relative costs of freshwater injection and saltwater pumping to benefits of freshwater production and represents the impact of various pumping and injection on the groundwater system

$$\alpha = -(\omega_1 d + \omega_2 a + \omega_3 i) \tag{2}$$

in which $d = V_D/A$ is the normalized average drawdown of freshwater head, $a = V_s/A$ is the normalized increase in saltwater intrusion area, $i = V_s/A$ and is the normalized increase in saltwater volume in the aquifer. are weighting factors for each index.

Lowering fresh groundwater head and intruding saltwater are considered negative impact. Saltwater intrusion results in enlargement of saltwater occupying area (A_s) on the aquifer bottom and increase in saltwater volume in the aquifer (V_s). In this case, α becomes a negative number. Opposite changes are considered positive (i.e. $\alpha > 0$), Fig. 1 illustrates these impacts. specifies the importance of impact.

Costs and penalties are to be minimized. The objective function becomes:

Minimize

$$\chi_n^2 = \omega_s \sum_{k=1}^{N_{pfo}+N_{pfe}} Q_{ps,k} + \omega_i \sum_{k=1}^{N_{ifo}} Q_{if,k} + \omega_c \sum_{k=1}^{N_c} Q_{c,k} + \omega_f \sum_{k=1}^{N_c} Q_{cf,k} \tag{3}$$

where $Q_{ps,k}$ is the rate of saltwater produced from k^{th} the freshwater pumping well; N_{pfe} is the number of existing freshwater pumping wells and $Q_{cf,k}$ is the freshwater production rate from a saltwater pumping well operating at $Q_{c,k}$. The following mass balance relationship holds for a saltwater pumping well:

$$Q_{c,k} = Q_{cs,k} + Q_{cf,k} \tag{4}$$

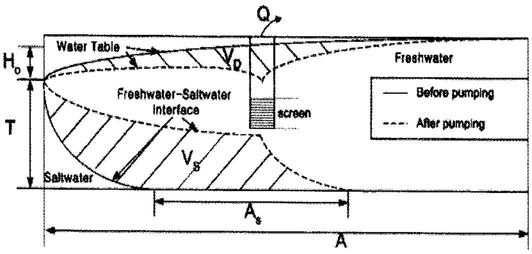

Fig. 1. Parameters representing impact on groundwater environment.

Table 1. Well types and respective elements of the objective function.

Component	Well type		Benefit	Cost	Penalty
FW	Pumping	New	O	-	O
		Existing	-	-	O
	Injecting		O	O	-

Penalty of freshwater pumping from saltwater pumping wells are made proportional to the sum of freshwater pumping rates from N_c saltwater pumping wells.

The two objective functions can be combined to yield the following single objective function:

Maximize $\chi^2 = \chi_x^2 - \chi_n^2$ (5)

The relationship between well types and components of the objective functions is presented in Table 1.

Simulation-optimization model

In this study, a modified version of the finite-element sharp-interface groundwater flow model developed by Huyarkon et al. (1996) is used to simulate freshwater and saltwater flow. The model offers numerous advantages over analytical solutions to handle more realistic problems that may involve irregular domain shapes, inhomogeneous aquifer properties, partially penetrating wells, flexible boundary conditions among others.

For the optimization a genetic algorithm is used. The algorithm is a heuristic method mimicking the natural process of evolution. The algorithm can escape from a local optimum unlike derivative-based optimization methods and can identify a near global optimal solution. However, the algorithm may suffer premature convergence and excessive number of function evaluations. In this study a binary coded algorithm is used.

Illustrative Example-Base Case

Hypothetical cross-sectional aquifer

A hypothetical unconfined aquifer is presented in Fig. 1 with A = 1000 m and T = 20 m. The bottom of the unconfined aquifer is 20 m below MSL and is considered impervious. Freshwater enters the aquifer at the rate of 0.0057874 kg/s through the inland boundary at x = 1000 m. Here the mass flux (kg/s) is preferred to the more traditional volume flux (e.g. m^3/d) for computational purposes since freshwater and saltwater differ in density. 1 kg/s of freshwater and saltwater flux are equivalent to $86.4\,m^3/d$ and $84.3\,m^3/d$, respectively when densities are 1000 and $1025\,kg/m^3$, respectively.

A non-uniform mesh is used. Smaller elements (minimum of 5 m long) are used near the coastline, and larger elements (up to 50 m long) are used near inland boundary. All together, 125 elements are used. For the problem considered, the toe of the freshwater-saltwater interface is located at x = 256 m in the absence of a well.

Optimal freshwater pumping rates

A groundwater-pumping problem using a partial penetration well is considered. The length of the screen is 10 m and is positioned 10 m above the aquifer bottom. The maximum pumping rate, which can be attained without the well being intruded by the saltwater, is the rate that may cause the freshwater-saltwater interface to rise up to right beneath the well. Intuitively, one would have to place the well farther upstream to be able to pump more freshwater.

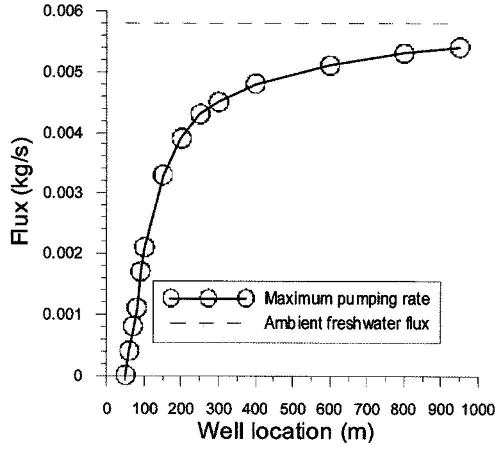

Fig. 2. Optimal pumping rates for various pumping well locations.

Maximum pumping rates for various pre-specified well locations, without causing saltwater contamination of the well, are computed. For the moment, the groundwater environment indices are not considered (i.e., $\omega_\alpha = 0$). For penalty of saltwater pumping, a value of 10 is used for ω_s. Results are depicted in Fig. 2. When the well is placed within 50 m of the coastline, no freshwater pumping is possible; the interface is too close to the well. When the well is moved inland, the maximum pumping rate gradually increases. When the well is placed at the inland boundary, the pumping rate can be raised to 0.0054 kg/s, about 93% of the ambient groundwater flow (0.005787 kg/s), without incurring saltwater intrusion at the well. Clearly, placement of a pumping well has significant impact on the amount of groundwater that can be withdrawn.

Impact on groundwater environment

In the previous section, the objective function is evaluated solely on the freshwater production rate. In this section, tradeoffs with impact on groundwater environment are studied. The balance between the two conflicting interests, freshwater production and impacts, is controlled by the weighting factor ω_α. A sensitivity analysis is carried out to investigate the effects. For this problem, both of the pumping rate and the well location are decision variables for the optimization problem. Computed results for pumping rates and well locations, and impact on groundwater environment are presented in Fig. 3 and Fig. 4, respectively.

Small values of ω_α imply freshwater production is more important. Thus the well is placed farther upstream to achieve maximum pumping rates (Fig. 3). Values of three indices show impact on groundwater environment (Fig. 4). Effective head is reduced by over 75% compared to the pre-pumping condition. Saltwater intrusion area is increased by nearly 75%, and the volume of saltwater is increased by over 55%. As it is expected, freshwater pumping degrades the quality of groundwater environment in all three aspects. Large values of ω_α place more weight in preserving the groundwater environment. The optimal well location is moved toward the coast, and the pumping rate is

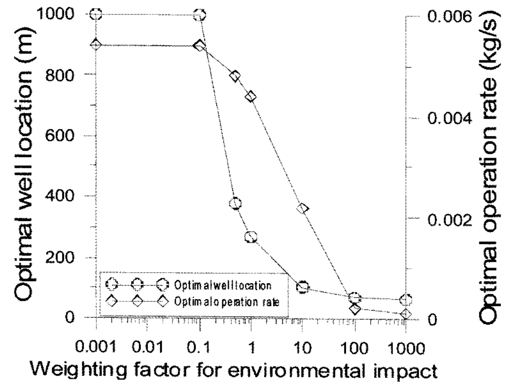

Fig. 3. Optimal pumping rates and well locations for various environmental weighting factors.

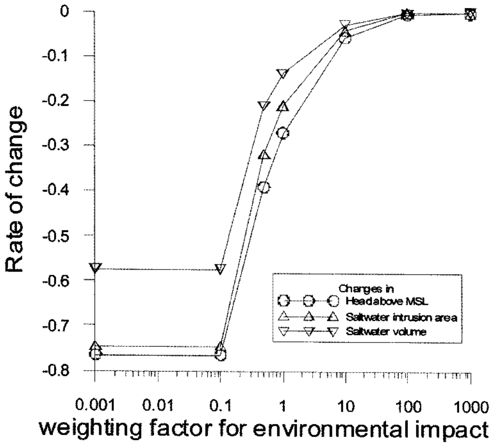

Fig. 4. Changes in environmental indices for various values of GWE weighting factor.

reduced. A well closer to the coastline causes less overall drawdown than a well upstream. Thus, when impact on environment is considered, a well near the coast is always preferred. As the values of ω_α are increased, impacts on the environment are also reduced, as it is evident from Fig. 4. When an extremely large value is used, the pumping rate is reduced to almost 0. Consequently, there is virtually no impact on the groundwater environment.

Over exploitation-saltwater contamination

To investigate effects of freshwater injection and saltwater pumping wells in controlling a saltwater wedge, a freshwater pumping well at a fixed location (x = 300 m) is considered. At this location, the maximum pumping rate that can be sustained without being contaminated by saltwater is 0.0045 kg/s. With this pumping rate, the toe is located at x = 490 m. Compared to the pre-pumping condition, advancement of nearly 240 m is observed.

To contaminate the well with saltwater, the pumping rate is raised to 0.005 kg/s from 0.0045 kg/s, 11% higher than the optimal pumping rate. This rate amounts to over 86% of the ambient freshwater flux. At this rate the well is contaminated: of 0.005 kg/s of total extraction, 4.6% (0.000229 kg/s) is saltwater which would make the water too salty for human consumption. In the following sections optimal operation rates and well locations of a freshwater injection well and saltwater pumping well are studied to recover the freshwater pumping well with the excessive operation rate.

Injection Well

Optimal injection rate

The following questions may arise regarding groundwater injection. How much net gain (i.e. the increased groundwater pumping rate less the injection rate) in freshwater production is possible by employing injection wells? Where and how much water does one have to inject to reclaim the saltwater contaminated wells? What are the effects on the saltwater wedge?

The first question is especially relevant when the injection water is as costly as groundwater produced. However, to the authors' best knowledge, no study has answered the first question. We attempt to answer the first question by solving the following problem : an optimization is carried out to determine the least injection rate and the corresponding injection location. If the required injection rate is less than the extra freshwater pumping rate (0.0005 kg/s) the use of an injection well does provide the net gain. For the moment environmental impacts are ignored.

The optimization model resulted in a unique injection rate of $Q_i = 0.0005$ kg/s and multiple optimal well locations: anywhere between x = 300 and 1000 m. For the cross-sectional aquifer, there is no net gain in the freshwater. To protect the freshwater pumping well, the interface must be lowered below the well tip. This requires that the freshwater head at the pumping location be higher than a critical value, which is established when the freshwater flux of 0.001287 kg/s (= 0.005787 − 0.0045 kg/s) is maintained between the freshwater pumping well and the coastline. When the pumping well operates higher by 0.0005 kg/s, the flux in the reach is reduced by the same rate. An injection well must supply the deficit to repel saltwater wedge at the pumping well.

Further optimizations are conducted to determine required injection rates for injection locations closer to the coastline. As the injection well is placed closer to the coastline, Fig. 5 indicates that larger injection is necessary: when the injection well is near the coastline (20 m), the required rate is over ten times that of the minimum injection rate at upstream locations. This observation is in conflict with the general practice of placing injection wells between freshwater pumping wells and the coastline. However, observations made from the cross sectional analysis cannot be generalized to areal problems, and a separate study is needed.

Optimal injection well location

Consideration of impacts on groundwater environment renders a unique solution for the optimal injection location. Fig. 6 depicts performances of the injection well, injecting at 0.0005 kg/s, for various locations. Clearly, effects of an injection well are opposite to those of a pumping well: quality of groundwater environment is improved in all three aspects as the injection well is placed farther upstream.

As the position of the injection well moves upstream all three indices improve monotonically. Therefore, the best injection well location is at the upstream end. Overall piezometric head build up increases from 1% to over 9%. The maximum improvements for the saltwater area and volume are roughly 2% and 1.5%, respectively. When the injection well is near the coastline, it affects more on saltwater volume than on saltwater area. Most of saltwater area reduction occurs between 300 m and 450 m. Therefore, separate consideration of area and volume is useful in assessing performances of an injection well.

When a different value is used for ω_α, values of the objective function would change, but not the location and injection rates.

Conclusions

An optimization model is developed for site-specific design of groundwater development and control of freshwater-saltwater interface. Injection and extraction

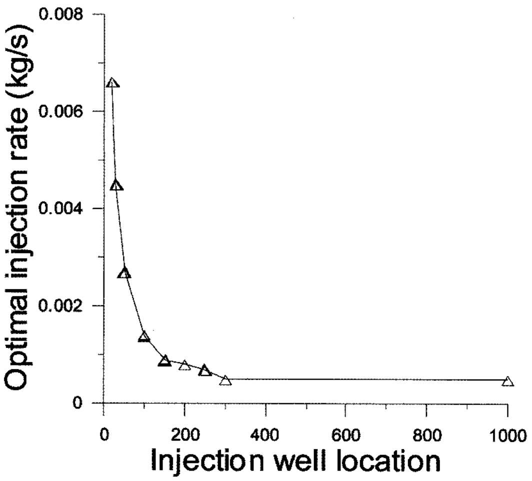

Fig. 5. Optimal injection rate for various injection well locations.

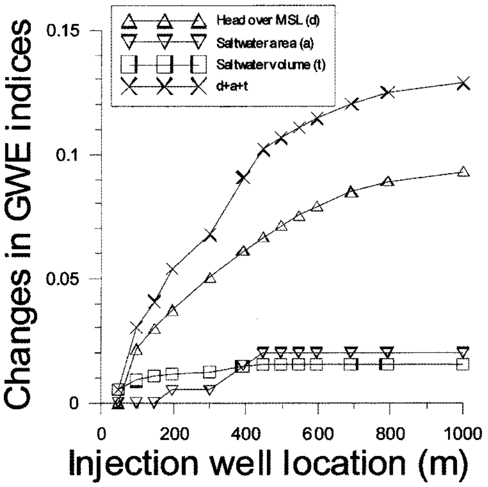

Fig. 6. Changes in GWE indices for various locations of injection well.

barrier well systems can be dealt with, and operation rates and locations of various wells are the design parameters. Positive and negative impacts of various wells on groundwater environment can be accounted for. Use of a numerical sharp-interface model enables applications to practical problems without unduly computational expense of a more rigorous density-dependent flow and transport model.

For groundwater development involving freshwater pumping wells only, optimal pumping rates and locations are found strongly dependent on the importance of groundwater environment. The model provides benefits and costs associated with each optimal pumping rate and location. Decision makers can analyze the tradeoffs between the candidates.

Example applications on a hypothetical cross-section aquifer reveal that an injection well is successful in reclaiming a saltwater contaminated freshwater pumping well. Required injection rate depends strongly on the injection location. Least is required when the injection well is placed upstream of a freshwater pumping well. When the injection well is positioned downstream of the pumping well, the injection rate increases significantly as the injection well approaches the coastline. Consideration of impacts on environment would suggest that the farthest upstream is best to place an injection well. Furthermore, injection wells in the vicinity of the coastline are effective only in reducing the saltwater volume. Upstream wells can reduce the extent of intrusion as well. However, observations made in this study are based on cross-sectional analyses and therefore, cannot be generalized to areal problems. Investigation on the areal problems is currently under way, and preliminary results indicate that effects of dimensionality is significant.

It is also noted that a sharp interface is an approximation of a transition zone of finite width. Therefore, the application of the simulation-optimization model should be limited to problems with sufficient length scales so that the thickness of the transition zone is not important. Although the sharp-interface model appears to predict saltwater content of a pumping well with reasonable accuracy, the Dupuit assumption does not hold when the vertical flow component is large. The genetic algorithm can only guarantee a near optimum solution. Caution must be exercised in examining model results.

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