

PREDICTION FINDING OPTIMUM LOCATION AND RECHARGE RATE OF WELLS TO PREVENT SALTWATER INTRUSION INTO THE COASTAL AQUIFERS

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Abstract: Although major part of the planet earth is covered by water, there are several limitations due to the quality and quantity issues as well as accessibility to the required time and place. When saltwater of sea or lakes enter adjacent aquifers, it leads to deterioration of the groundwater quality such that it would become undrinkable for human beings and detrimental for agricultural crops. Most of the lakes are placed for collecting superficial and groundwater of their surrounding basins. Therefore, they might contain polluted water. Pollutant ions may enter adjacent aquifers with the saltwater. One reliable method to control saltwater intrusion is to artificially recharge the coastal aquifers through distribution of water in surface pools for unconfined aquifers and recharge wells for confined ones. In a condition, where it is possible to provide water resource in some seasons of year (surface water due to winter rainfalls), artificial recharge can be used to raise water table and prevent saltwater intrusion. However, it must be noted that construction and utilization of the artificial recharge facilities might not be economic when rate of recharging of the aquifer is not adjusted optimally. This study aims to propose a pattern of controlling saltwater intrusion with minimum costs for a real aquifer in practice. In this regard, MODFLOW software was utilized for simulation while ant colony optimization algorithm linked to MODFLOW software used to optimize costs of the recharging operation. The index to evaluate reduction percent of the saltwater intrusion level in this problem was the Kashef analytical relation. Meanwhile, reduction of construction costs for recharge wells and also recharging of freshwater during time were considered as the target functions with 50% reduction saltwater wedge being the only constraint of this problem.

KEYWORDS: Saltwater intrusion, Saltwater wedge, MODFLOW software, Recharge well, Ant colony optimization algorithm, Coastal aquifer.

1. INRODUCTION

Most of the analyses of controlling methods which mitigate the detrimental effects of saltwater intrusion are still just at research level and no specific practical guideline has been established so far to act in favor of groundwater resources in coastal aquifers. Some analytical methods have been recently introduced specially for designing recharge wells which delay saltwater intrusion or cause formation of hydraulic barriers. Technical features of these methods have been investigated in previous works and their economic issues will be studied here.

If a set of recharge wells are placed along the coast, the aquifer under particular conditions will cause creation of a combined effect of flow which is associated with a uniform increase in the natural flow (and causes a uniform change in the saltwater wedge). Thereby, it would be possible to adjust saltwater wedge by altering location of recharge wells and rate of recharge for wells. Taking into account the immiscible nature of liquids (saltwater and freshwater) (i.e. diffusion due to water recharge is negligible) and small size of the transformation region in which diffusion and emission is occurred, then the natural interface between saltwater and freshwater (in confined and unconfined aquifers affected by natural flow) will appear inside the aquifer (Canales et al., 2001). In an article entitled "Evaluating Risk of Saltwater Intrusion in Northeast Mexico" they used geological and geophysical studies to locate the saltwater zone in aquifers then employed hydraugeochemical studies to study the unusual increase of electric current (EC) and chlorine ion (Cl-) in some coastal wells with permeability of saltwater in the aquifer. Hozhaj (2005) was able to confirm saltwater intrusion into northern aquifers of Albania based on observations of chlorine ion concentration in five sample wells as well as relevant hydraugelochemical studies. Afterwards, they calculated hydraulic head and chlorine ion concentration using SUTRA software on a 3D model according to time and place development. The computed values which he obtained from changing the indexes of aquifer revealed a great agreement with the observed data.

Khalil (2006) used total number of 60 vertical electrical sounding in a Schlumberger array to investigate saltwater intrusion in Abu Zenima, Western Sina Peninsula, Egypt. Having benefited from resistivity maps, he was able to specify border of saltwater and freshwater. Randall and Gibbison (2006) in another research entitled "Saltwater Intrusion and Protective Activities against Them in Southeast Georgia" verified intrusion of saltwater using 2-variabed diagrams regarding the environmental consequences of this phenomenon on coastal aquifers.

Various techniques have been proposed so far to control saltwater intrusion. Todd (1974) first introduced different methods to prevent pollution of saltwater including decreasing rate of pumping, movement of pumping wells, application of underground dams, natural and artificial recharge to aquifer, abstraction of saltwater from aquifer and a combination of abovementioned methods. Scholze (2002) suggested a technique in order to contribute to control seawater. He abstracted saltwater from aquifer and discharged it into sea in order to reduce concentration of saltwater in the aquifer. The

same method was also proposed by Hamza and Sherif (2002). Recharging freshwater and abstraction of saltwater from aquifer was a combined method introduced by Mahesha (1996) and Rostagi (2004). By this operation, concentration of saltwater will be decreased in the aquifer while concentration of freshwater will be increased there. Abd-Elhamid and Javadi (2011) have more recently proposed a method comprised of three steps, namely abstraction of saltwater from salty zone, desalination from saltwater using reverse osmosis process, and finally recharging the desalinated water into the aquifer.

A few previous studies have been implemented using simulated models to control saltwater. Rather, most of them were conducted by trial and error in order to find the best points for location of pumping and recharge wells. They used to investigate the effect of recharge, pumping and a combination of these two on the amount of saltwater intrusion. Kashef (1976) studied the effect of recharge wells with a rather different location pattern on the amount of salinity reduction within a confined aquifer. The recharge wells were placed in parallel with the coastal line in different distance from each other with each well working at a different rate of flow. He utilized 3D finite element to simulate the aquifer. Then, he considered various conditions by changing the distance between wells, the rate of flow, and the time of recharge operation. He finally concluded that the optimum location of recharge wells is 0.6 to 1 times that of initial length of saltwater wedge. Kacimov (2008) used pumping the saltwater between level of saltwater and level of freshwater in aquifer to limit expansion of saltwater wedge. He used SUTRA software to study the aquifer under various pumping scenarios in vertical scale and eventually concluded that the problem of saltwater intrusion can be controlled by a correct method of pumping the saltwater in the aquifer.

2. METHODOLOGY

The method introduced in this respect was proposed to optimize costs of recharging freshwater into recharge wells. Bigger rate of flow in recharging wells will further increase the piezometric head in the aquifer and directs the saltwater wedge towards the sea with a rather longer length. However, increased rate of flow during this recharging can lead to additional costs of the operation. This issue can be transformed to a single-objective problem considering a two management model whose main purpose is to decrease the rate of flow and find the optimum place for recharge wells (reducing costs of recharge operation) on the aquifer. For this purpose, MODFLOW software was used to simulate the aquifer while two-objective Ants Colony Optimization (ACO) Algorithm was applied to optimize the location and recharge rate of wells. The index to evaluate reduction percent of the saltwater wedge in this problem was Kashef's analytical relation. Meanwhile, efficiency of the proposed method was evaluated on a confined aquifer in Florida and its relevant results were reported as well. Briefly, the method of experiments in this research was such that the optimization model searches within the results of software which are presented in piezometric points of the aquifer to find the location having the minimum costs. The experimental method has been demonstrated in Fig. 1 by a flowchart.

P standard whose value is determined by the user and was assumed 50% in this problem will be applied as a constraint. Specific standards are used to reduce saltwater wedge by 50% in the two-objective optimization model. The aim of this model is to minimize costs of the construction. The abovementioned optimization mathematically can be given as follows:

$$P_{\text{ondc}} = \sum \sum p_{\text{ondcij}} A \quad (1)$$

$$P < \text{standard}$$

$$q < q_{\text{max}}$$

$$P = g(x, y, q) \quad (2)$$

where,

pondc: total costs of recharging freshwater and construction of wells,

q: rate of flow into wells,

p: reduction percent of saltwater level,

x: distance of well from coastal line,

y: distance of well from marginal boundaries of aquifer,

3. ANTS COLONY OPTIMIZATION (ACO)

Various methods have been suggested so far to solve the optimization model. Some of these methods can just find absolute optimum answers while the others are only limited to find good answers. Finding absolute optimum answers is rather difficult in solving some optimization problems and need great deals of calculation time and cost. Therefore it seems necessary to propose methods which are able to reach somewhat optimum (and not absolutely optimum) answers. Ants System (AS) algorithm was first introduced in 1992 by Dorigo to solve TSP problems. Crodon and his coworkers provided some guidelines to solve a problem using ACO. Ants are insects; they live socially and are able to demonstrate complicated behaviors due to their developed relations and perform difficult tasks which are impossible to be done by a single ant. Finding the shortest path between nest and food source, or sharing tasks in their society are some examples of these tasks.

Experiments have proved that ants are able to reconnect the shortest path. When a barrier is placed along their path, the ants will gather opposite the barrier and since there is no pheromone on both sides, they may choose both paths with the same probability.

The smaller time difference along the shorter path will cause the ants which have accidentally selected the shortest path to drop pheromone more quickly. The pheromone of the shorter path will be stronger than the longer path due to the more number of ants passing through it. Thus, after a short while, all ants will choose the shorter path to pass (Pasteels et al., 1987). Artificial pheromone is used in ACO algorithms to find the optimum answer like the real process of food seeking by ants. The artificial pheromone is indeed a real number of τ which is allocated to the choices selectable by an artificial ant in producing the answer. For example, in the shortest problem a pheromone amount of τ_{ij}

is given to each path of (i,j) which indicates desirability of this path. An ant located in node i will choose its next node based on the relative accident transport as follows:

$$p_{ij} = \tau_{ij} / \sum \tau_{ij} \quad (3)$$

Where, p_{ij} is the probability of selecting node i by the ant which has reached node i . As observed in the equation above, the large amounts of pheromone on path ij will increase the probability of choosing the path which is very similar to the function of real ants. In addition to pheromone, one heuristic component can be used in many problems in order to yield variable answers. In fact, the heuristic component contributes to choosing the path like an artificial eye. This artificial eye would help ants to select the correct path. The relation of relative accident transport can be rewritten as follows:

$$p_{ij} = (\tau_{ij}^\alpha \eta_{ij}^\beta) / (\sum_{hes} \tau_{ij} \eta_{ij}^\beta) \quad (4)$$

Where, η_{ij} is the heuristic component. Larger amounts of heuristic component will increase the probability of choosing a specific path. The amount of η_{ij} is determined by various methods depending on the type of problem. For example, a practical form of it can be defined as $\eta_{ij} = 1/d_{ij}$ for a TSP problem in which d_{ij} is the weight of ij path or the distance between customer i and customer j (Bobabeau et al., 1999).

Synchronization of pheromone will increase the concentration of seeking process for ants on the correct area of search space. Thus, it is expected that much more desired answers will be produced by more concentrated search in that area (Jalali, 2005).

$$\tau_{ij} \rightarrow (1-\rho) \cdot \tau_{ij} + \Delta_{ij} \quad (5)$$

Where, $\rho \in (1,0)$ is a parameter which indicates the amount of losing pheromone in each period. Δ_{ij} is a heuristic value which will be equal to zero if the path (i,j) is not roamed by the ant. For optimization of the recharge cost which is a function of wells' location and rate of flow, the distance of wells and the rate of flow is increased in 5 m and 0.1 m³/s steps, respectively while the ants passing discrete paths to reach the location and rate of flow with the minimum cost (Fig. 2).

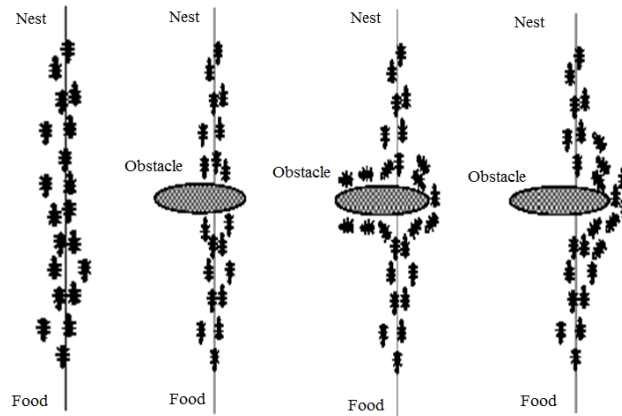


Fig. 1 Crossing Path of Artificial Ants

4. GOVERNING EQUATION OF PUMPING WELLS

It can simply be demonstrated that the hydraulic potentials along the upper border of aquifer are a bit smaller than those along the interface. Therefore, combination of natural and forced effects such as water pumping should be preferentially selected based on the potentials along the upper border in order to provide a safety margin. Thus, the natural conditions are determined according to the Kashef's relations for potential of various points in the confined aquifer like below:

$$H^* = \sqrt{X + \beta W [\delta(x_w - x)^2 + (y_w - y)^2]} \quad (x \leq 1.0) \quad (6)$$

$$H^* = 1/2(1+x) + \beta W [\delta(x_w - x)^2 + (y_w - y)^2] \quad (x > 1.0) \quad (7)$$

where,

H^* : dimensionless potential,

δ : dimensionless factor of time,

x, y : distance from each point to center of well,

W : place factor.

If H^* calculated from Kashef's equations is greater than 1.0, then the artesian aquifer is completely located within the area of freshwater. however when $0 < H^* < 1.0$ then both saltwater and freshwater can exist there. As a result, the line of $H^* = 1.0$ gives the border between these two areas. Location of pumping wells and rate of recharge for wells must be designed in MODFLOW software such that H^* in half saltwater wedge (an area where salinity should be near zero) becomes larger than 1.0.

5. SIMULATION OF BISCAYNE AQUIFER

Physical properties of soil and aquifer from the work represented by Al-Hamid have been summarized in Table 1. It can be seen from Figs. 3 and 4 that the boundary conditions of the aquifer is formed from a constant head of water in the northern side which reaches the sea and a constant head in the southern side of aquifer which is 56 cm higher than sea level. The aquifer is 300 m long and 30 m deep. Previous studies have considered Biscayne aquifer with unit width this research, however assumes an aquifer of 200 m width to be simulated in the software. The size of mesh in this software was $5\text{m} \times 5\text{m}$ with the aquifer being divided into 2400 elements.

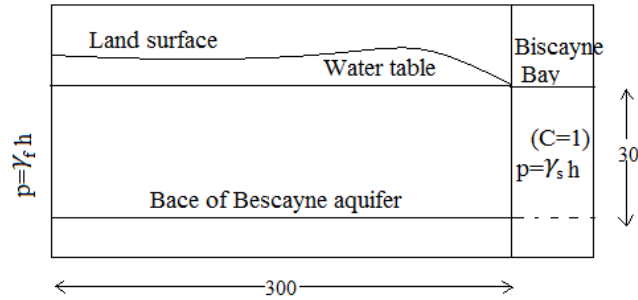


Fig. 2 Cross-Section and Dimensions of Biscayne Aquifer(Abd-Elhamid, Javadi)

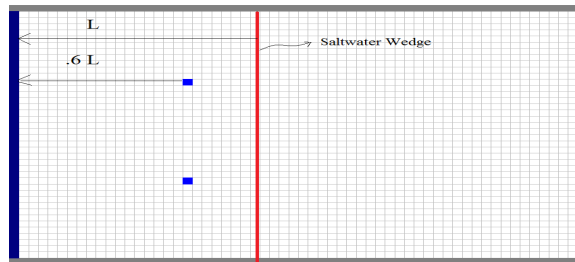


Fig. 3 Meshing and Location of Recharge Wells in MODFLOW software

Table 1. Physical Properties of Soil and Biscayne Aquifer

Property	Value
Molecular Diffusivity (Dm)	$6.6 \times 10^{-6} \text{ (m}^2/\text{s)}$
Length Dispersion (αL)	0(m)
Porosity (N)	0.39
Liquid Viscosity (M)	0.001 (kg/m)
Rate of Flow Passing the Aquifer (Qin)	$1.68 \times 10^{-4} \text{ (m}^3/\text{s)}$
Gravity Acceleration (g)	$9.81 \text{ (m/s}^2)$
Density of Freshwater (ρ_w)	1000(kgm^{-3})
density of Seawater (ρ_s)	1025(kgm^{-3})
Hydraulic Conductivity	$3 \times 10^{-3} \text{ (m/s)}$
Permeability (K)	$3 \times 10^{-10} \text{ m}^2$

Table 2. Optimum Results Obtained from Software for Wells' Rate of Recharge in m³/s

Recharge Time	Optimum Location	Optimum Location
	X _w =.6	X _w =6
	S=200	S=100
t=10s	1.60	0.28
t=1min	0.19	0.07
t=4min	0.10	0.04
t=0.5h	0.08	0.03
t=0.5day	0.08	0.03
t=1day	0.08	0.03
t=5day	0.08	0.03
t=20day	0.08	0.03

6. RESULT AND DISCUSSION

Rate of flow for recharge wells was a function of distance between wells and time of recharge. It is obvious that by increasing the time of recharge, the radius of effect is increased while the rate of flow is decreased for the wells. Having reached the wells to stable conditions, the rate of flow will approach to a constant value. Based on analytical relations, the length of saltwater wedge was measured as 190 m. Other specifications related to the rate of flow in recharge wells based on time and cost of recharge operation listed in Tables 2 and 3, respectively. The distance between wells (s) has been considered for two different states while the optimum location of recharge wells X_w is determined to be in 60% distance from the saltwater wedge.

Table 3. Optimum Results Obtained from Software for Wells' Rate of Flow in m³/s

Number of wells in the width of aquifer	rate of flow (m ³ /s)	cost of well construction (US \$)	total costs (US \$)
1	0.08	30,000	6,330,000
2	0.06	60,000	4,790,000

6. CONCLUSION

One of the common ways to control saltwater intrusion into aquifers in water industries is artificial recharge for increasing balance of groundwater along the coastal line. As mentioned previously, it is possible to raise the level of water table by artificial recharge and meanwhile prevent marching of saltwater toward the land. Although freshwater

recharge is known as the best method both qualitatively and quantitatively, it can make construction and utilization of artificial recharge facilities totally uneconomic if the rate of recharge into aquifer is not properly optimized. Kashef investigated the effect of recharge wells having various location patterns on reduction of salinity in a confined aquifer and discovered that the distance between wells and also rate of pumping controls the saltwater wedge. Moreover, the optimum location of recharge wells is found to be 0.6 to 1 times that of initial saltwater wedge. In all these conditions, various combinations of Q , t , S and X_w could be obtained. The recharge operation must continue until the potential of points reach a constant head for each condition. The results of this research revealed that to limit the area of saltwater intrusion to 50% by recharge wells, the optimum location of recharge wells must be within 0.6 of the saltwater wedge. It was also demonstrated that construction of recharge wells in parallel arrangement to with small distance or lower recharge rate of flow would be more economic if based on technical principles of aquifers. Moreover, if the time of freshwater recharge is further increased, the rate of flow will be decreased for the aquifer under study having a typical salty wedge of 190 m long. In the method adopted in this study for longer times of recharge (time factor becomes smaller than 0.1), the recharge rate of flow will converge toward the passage rate of flow from the aquifer with the location of recharge wells being ineffective on their rate of flow.

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