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Optimal Dewatering System in Subsurface Zone Using Bacterial Foraging Technique

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ABSTRACT: Ground water flow modeling and optimization techniques are coupled to determine the optimal cost of pumping to reduce the groundwater table of a confined aquifer at steady state condition. An optimal aquifer pumping model employing a non-linear programming was developed to find the minimum cost of pumping in a confined aquifer at steady state. The non-linear model include two objective functions: minimizing the cost of pumping and maximizing the discharge from the aquifer. Bacterial Foraging Techniques (BFT) is used to optimize the cost function The cost of pumping includes the fixed cost of system construction and installation as well as operation and maintenance. Results show that fixed costs has significant impact on the cost of aquifer pumping system. The sensitivities of different parameters such as cost of pumping and pumping discharge to variations in the permeability of soil and drawdown are studied by varying K and $S(k)$ over wide range.

INTRODUCTION

With the aid of modern scientific research and developments in construction technology, new construction projects have expanded in response to increasing world population and industrialization. Due to the acceleration in constructional works, suitable areas for construction have diminished, resulting in selection of less appropriate sites with foundation problems. High ground water tables are one of the most frequently encountered foundation problems, requiring deep excavations in pervious soils below the water table. To obtain the best working conditions and slope stability, appropriate dewatering systems are safer and more economical when compared with other methods for sites requiring deep excavations below the water table. The magnitude and cost of a dewatering project depend on the size and depth of the required excavation and the length of time the dewatered condition must be maintained. Optimization models have been widely used to solve groundwater problems over the past two decades. These models have been used to identify optimal pumping strategies and cost effective scenarios under the consideration of groundwater hydraulics and water-quality restrictions. In order to achieve this, groundwater simulation models are often combined with optimization models by means of various techniques.

A variety of optimization techniques have been applied to optimal groundwater remediation or pumping design problems. These include linear programming (Atwood and Gorelick, 1985), non-linear programming (McKinney, 1996), dynamic programming (Culver, 1993), simulated annealing (Marryott, 1993), and genetic algorithms. However the majority of these works relies on traditional non linear algorithms. The basic draw back of these traditional algorithms is that they get struck with the local minima and hence giving erroneous results. Hence in this study Bacterial foraging techniques is adapted to assist in the deciding the optimal pumping strategies. Klěvin passino (2000) modelled foraging process as an optimization process where an animal seeks to maximize energy obtained per unit time spent foraging. Search strategies form the basic foundation for foraging decisions. In their study, the chemotactic behaviour of E. coli, i.e., how it forages is explained and a computer program that emulates its foraging optimization process is presented and applied to solve a function minimization problem

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and hence it is explained how bio-mimicry of bacterial foraging can be used to provide adaptive control strategies, and methods for distributed coordination and control of autonomous vehicles. Liu *et al.* (2002) explained the social foraging behavior of E. coli and M. xanthus bacteria and developed the simulation models based on the principles of foraging theory that view foraging as optimization. This provides a set of novel models of their foraging behaviour and with new methods for distributed non gradient optimization. Moreover, they showed that the models of both species of bacteria exhibit the property identified by Grunbaum that postulates that their foraging is social in order to be able to climb noisy gradients in nutrients. This provides a connection between evolutionary forces in social foraging and distributed non gradient optimization algorithm design for global optimization over noisy surfaces. Further Liu *et al.* (2004) characterized swarm cohesiveness as a stability property and use a Lyapunov approach to develop conditions under which local agent actions will lead to cohesive foraging even in the presence of "noise" characterized by uncertainty on sensing other agent's position and velocity, and in sensing nutrients that each agent is foraging for. The results quantify earlier claims that social foraging is in a certain sense superior to individual foraging when noise is present, and provide clear connections between local agent- agent interactions and emergent group behaviour. Moreover, the simulations show that very complicated but orderly group behaviours, reminiscent of those seen in biology, emerge in the presence of noise.

GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

A mathematical groundwater water model for steady state conditions consists of a governing equation and boundary conditions which simulates the flow of groundwater. Solving the model requires calculating the head at each point in the aquifer. The governing equation for steady state homogenous and isotropic confined aquifer of constant thickness is,

$$\frac{\partial^2 h(x,y)}{\partial x^2}+\frac{\partial^2 h(x,y)}{\partial y^2}=\frac{Q}{T} \quad \ldots (1)$$

Where $h(x, y)$ represents head of the aquifer at x and y coordinates in the aquifer.

The governing equation is subjected to boundary conditions. Figure 1 illustrates the hypothetical study area. The homogeneous aquifer has 4 wells as shown in the Figure 1 each at distance of 60 m. Since the entire area is symmetric only one fourth of the area is considered for simulation and the drawdown values for remaining parts of the aquifer were taken as the mirror values. To the north and east are fixed head boundaries of 30 m on each side. To the west and south are no-flow boundaries.

SIMULATION MODEL

The governing equation 1 is solved by using finite difference techniques.In the finite difference method a set of partial differential equations is replaced by algebraic equations which are amenable to solution on a digital computer. The finite difference methods are divided in to two main categories namely explicit method and implicit method. Forward difference technique is explicit method. Backward difference method and Crank Nicholson methods are implicit methods. In the explicit methods through computationally simple, suffers from a restriction on the size of the time step. There fore, it is no widely adapted. Implicit method is unconditionally stable and hence it has been adapted in this study. Figure 2 depicts the finite difference grid and the computational molecules,

$$\frac{h_{i-1,j}+h_{i+1,j}-2h_{i,j}}{\Delta x^2}+\frac{h_{i,j+1}+h_{i,j-1}-2h_{i,j}}{\Delta y^2}=\frac{Q}{T} \quad \ldots (2)$$

Where, $T = kb$

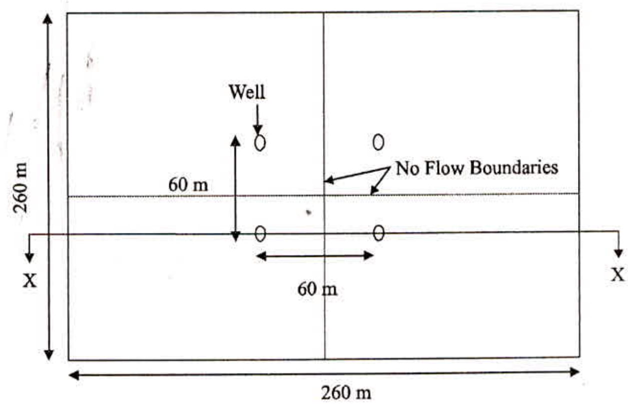


Fig. 1: Hypothetical site area and well locations

MODEL VALIDATION

Next, the one-dimensional model developed is validated by using an TWO-Dimensional Analytic groundwater flow model TWODAN was used. The analytic element model theory was developed by O. Strack (1989). For many applications, the analytic element model is more accurate and efficient than traditional numerical models of finite-difference or finite-element models. analytic element model can provide unlimited resolution over infinitely large flow domains, while simulating complex hydrogeological features, such as areas of heterogeneity in hydraulic conductivity and/or aquifer thickness, porosity, multi-layers or stratifications, and confined/unconfined or transitional aquifers. Application of the finite-element or finite-element models in regional-scale modeling would forfeit the ability to render high-resolution outputs within the local area. Analytic element model models with high resolution provide much more accurate results than conventional numerical models in large-hydraulic-stress situations that are a part of common remedial systems such as pumping, injection, trench, slurry wall and low permeability barriers. Table 1 and Figure 3 depicts that the results obtained from the calibrated TWODAN model matches well with simulated model developed.

Table 1: Summary of Results for Confined Aquifer of 10 m Depth at Steady State Condition

Out put Results	*Water Level at Each Well Location in m*	*Discharge from Each Well in m^3/day*
TWODAN	10.15	200.2
Simulated model	10.2	182

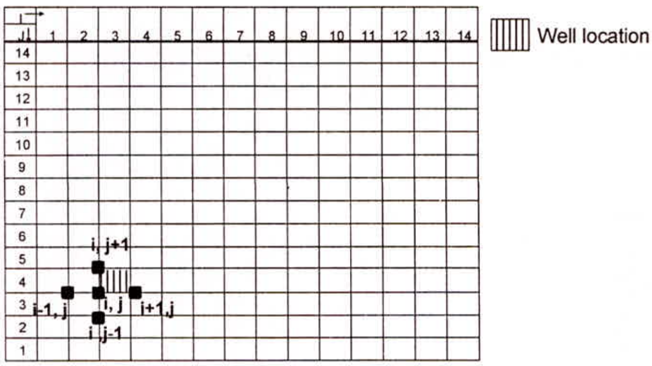


Fig. 2: Finite difference grid and computational molecule

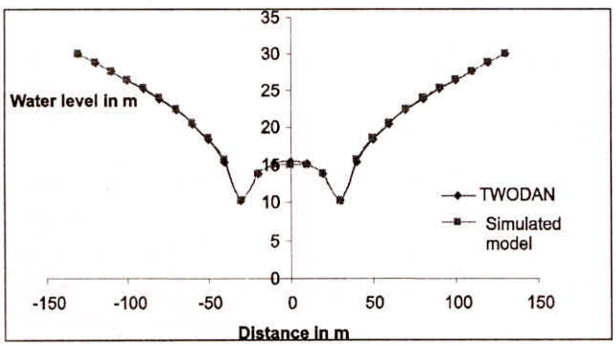


Fig. 3: Water table profile for confined aquifer at steady state

SENSITIVITY ANALYSIS

A sensitivity analysis is to identify key parameters that have most significant effect on influence on the total amount of cost of the project. The parameters analyzed include hydraulic conductivity, pumping discharge. To study the sensitivity of the total amount of cost of project and the pumping required from each well the parameters under consideration are perturbed keeping all the other parameters constant. Thus equation 1 is simulated first using the perturbed values of model parameters. Permeability values are taken within range of 0.5 m/day to 2.5 m/day. It is observed that the cost of pumping and the amount of pumping increases with the amount of draw down required increases. Figures 4 and 5 illustrate that if the amount of pumping is same for different permeability soils then the cost of pumping is almost same. The relation between cost and the pumping is not linear. As pumping increases, the cost is not varying linearly, this shows that there exits a non linear relation between cost and pumping. Hence ordinary linear formulation techniques don't yield the desired results. Hence the advanced heuristic techniques such as bacterial foraging technique is employed for solving the objective function.

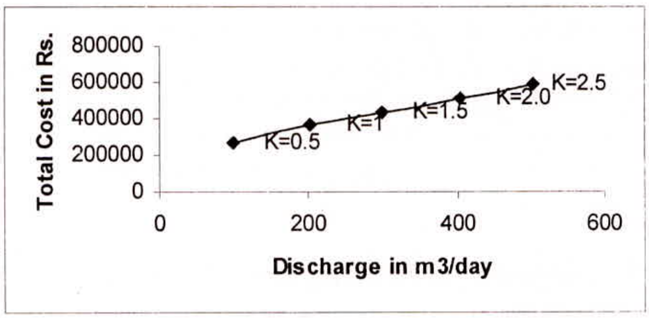


Fig. 4: Variation of cost and pumping with different permeabilities

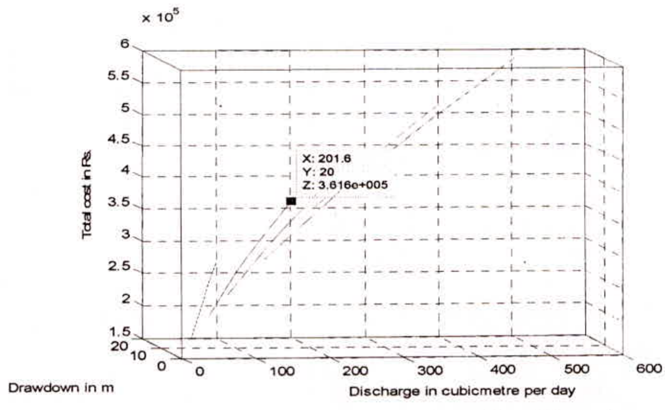


Fig. 5: Variation of cost and pumping with different permeabilities at different depths

BACTERIAL FORAGING TECHNIQUE (BFT)

Bio-mimicry of foraging activities of Bacteria such as the E-coli provides a robust algorithm for distributed non-gradient global optimization. Natural selection tends to eliminate animals with poor foraging strategies and favour those that have good food locating and foraging capabilities through reproduction. Over a period of time the entire population comprised of only the fittest animals (those having the best food gathering ability). Generally, a foraging strategy involves finding a patch of food, deciding whether to enter the patch to search for food and when to leave the patch. Bacteria like the E-coli use the salutatory approach to foraging. They move about a region changing directions and stopping wherever there is a good concentration of food. The E-coli bacteria using its flagella can either run (move straight) or tumble (change direction). These allowable movements of the bacteria comprise the following:

1. If in a neutral medium (one not too rich in nutrients), they alternate between runningand tumbling.
2. If swimming up a nutrient gradient, they swim longer, in order to seek increasingly favorable environments.
3. If swimming down a nutrient gradient, they search, avoid unfavorable environments.

We begin by assuming that μ is the instantaneous position of a bacterium. Then $G(\mu)$□R_P ,, represents an attractant profile, i.e. where nutrients are present, or the medium is neutral or noxious for $G < O$, $C = O$, $G > 0$ respectively. And p is the dimensional spread of $G(O)$, i.e. the number of parameters for optimization. Let, $P(j, k, l) = [\mu^i(j, k, l),\ i = 1, 2, 3, : : :N_b]$ represent the position of each member in a population of NB bacteria at the jth chemotactic step, kth reproduction step and the l^{th} elimination-dispersal event. Further, let $G(i, j, k, l)$ denote the cost at the location of the i^{th} bacterium $j\mu^{ii}(j, k, l)$ □R_P . To represent a tumble, a unit length random direction, say $\acute{A}(j)$, is generated then,

$$\mu^i(j + 1, k, l) = \mu^i(j, k, l) + v(i)\acute{A}(j)$$

Such that a step of size $v(i)$ is taken in the direction $(\acute{A}(j)$. If the cost of $G(i, j + l, k, l)$ is better at $\mu^i(j + l, k, l)$ than at $\mu^i(j, k, l)$ then another chemotactic step of size $v(i)$ is taken in that direction and this may go on up to a maximum of N_s steps.

OPTIMIZATION MODEL FORMULATION

An optimization model was developed to minimize the total cost of dewatering in the confined aquifer to reduce the water table level. The simulated model of the aquifer system was linked to the optimization model using the embedded technique. It was assumed that pumping occurs from four wells. Bacterial foraging technique was employed to maximize the total pumping rates and minimizing the total cost pumping from these four wells subject to hydraulic and drawdown limitations. The objective function of the model minimizes the total well completion cost and maximizes the total pumping from the wells, that is,

Minimize

$$C = \sum_{i=1}^{4} a_1 d_i + a_2 (Q_i)^{b_1} (d_i - h_i)^{b_2} + a_3 Q_i h_i - \lambda \sum_{j=1}^{4} Q(j) \quad \dots (3)$$

Where a_1, a_2, $a_3 b_1$ and b_2 are constant coefficients

Q_i = pumping rate of wells at location i (L^3/T)

d_i = depths of wells at location i (L)

h_i = the hydraulic head at location i (L)

λ = weighting factor representing the relative weighting of the well completion costs and total pumping, which is an assumed surrogate for the pumping costs.

The constraints of the objective function include the following:

1. Drawdown limitations,

$$S(k) \le S_{\max}(k)\ k = 1, \dots, 4 \quad \dots (4)$$

Where $S_{\max}(k)$ =maximum allowable drawdown at the pumping well k.

The maximum allowable drawdown was assumed to be 20 m at each pumping well.

2. Upper and lower limits on pumping rates of the wells,

$$0 \le Q(k) \le Q_{\max}(k)\ k = 1, \dots, 4 \quad \dots (5)$$

Where $Q_{\max}(k)$ = maximum pumping capacity of the pumping well k. The maximum pumping rate was assumed to be 500 m^3/d for all the pumping wells.

CONSTRAINT HANDLING IN BFT

A non-stationary, multi-stage Penalty Function Method (PFM) is adapted for constraint handling with BFT. Penalty function methods require the fine-tuning of the penalty function parameters, to discourage premature convergence, whilst maintaining an emphasis on optimality. This penalty function method, when implemented with BFT, requires a rigorous checking process after evaluation of the objective function to ascertain the extent of any constraint, violations, followed by the assignment and summation of any penalties applied,

$$\text{minimize } F(z) = f(z) + h(k) * H(z) \quad \ldots (6)$$

Where $f(z)$ is the original objective function as given in the (3),

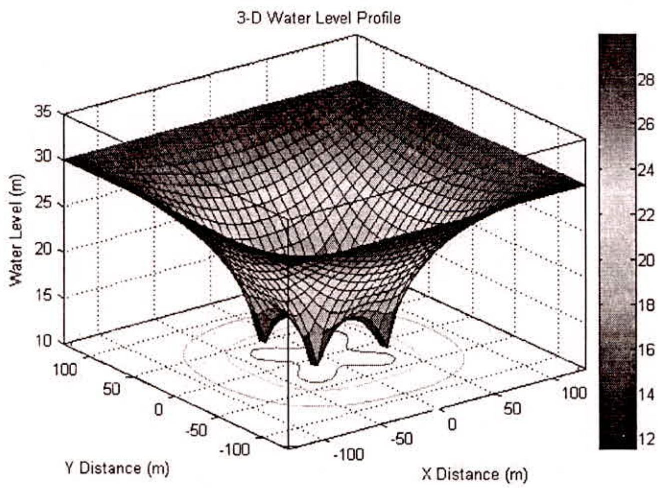
$$H(z) = \sum_{i=1}^{m} \theta(q_i(x)) q_i(x)^{\gamma(q_i(x))} \quad \ldots (7)$$

Where $q_i = \max\{o, g_i(x)\} i = 1, 2, 3, \ldots, m, g_i(x)$ are the constraints, $q_i(x)$is a relative violated function of the constraints.

$\theta_i(q_i(x))$ is an assignment function and $\gamma_i(q_i(x))$ is the power of the penalty function. Constraint violation is considered only when $g_i(x) > 10^{-5}$.

Table 2: Optimal Cost Values

Drawdown at Each Well Location in m	*Optimum Total Cost in Rs./Yr.*	*Optimal Discharge in m^3/day*
5	208110	50.39
10	267590	100.786
15	317120	151.18
20	361610	201.57



CONCLUSIONS

In this study ground water flow is modelled through saturated medium in confined aquifer at steady state. For modeling flow through soil a finite difference model is developed by using the technique of back ward difference technique to solve the flow equation and it has been validated using TWODAN. During validation the maximum error occurred is around 0.015%. A three-dimensional model was necessary to take fully into consideration the complex natural and artificial (e.g., protection low permeability barrier and re injection ditches) features of the subsurface system. Besides this the simulated model is embedded with BFT to obtain the optimal cost and the pumping discharge from each well to reduce the water level of the area. We have divided the total cost in to three parts, namely cost of drilling, cost of equipment and cost of operation and maintenance cost. In all of the costs the drilling and equipment costs are one time investment cost, where as the cost of operation and maintenance is variable with time. Sensitivity analysis is performed to analyze the sensitivity of the cost of pumping and the amount of pumping to variations with permeability values ranging from course sand to fine sand and with the amount of drawdown required. It is observed that both the cost of pumping and amount of required pumping are increasing with increasing the values of permeability and drawdown. Table 2 shows the optimal cost values obtained from the optimization model. The combined use of a numerical simulation model with an optimization non linear programming procedure has proven as a valuable tool in the analysis and design of a dewatering scheme.

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