Mansoura Engineering Journal, (MEJ), Vol. 29, No. 4, December 2004. C. 15

Reliability in Multi-Objective Management of Saltwater Intrusion under Uncertainty of Hydraulic Conductivities

الاعتماد على إدارة متعددة الأهداف للتحكم في تداخل المياه المالحة مع الشك في قيم معاملات التوصيل الهيدروليكية

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خلاصة

يهتم هذا البحث بدراسة درجة الثقة المرتبطة بإدارة الخزانات الجوفية الساحلية والتي لها خصائص هيدروليكية عشوائية وذلك مع تعظيم الاستفادة المرجوة من مجموعة من الأهداف المتضاربة. وقد استخدمت طريقة العناصر المحددة لتمثيل سريان المياه الجوفية وذلك تحت ظروف سريان مستقر داخل أي خزان جوفي مخلق غير متجانس. واستغلت معادلة ستراك لتحويل المعادلة غير الخطية المتحكمة في السريان إلي معادلة خطية. كما استخدمت طريقة LU التفكيكية وذلك لقلب المصفوفة الرئيسية بالنموذج بغرض الحد من الزمن المطلوب للحسابات. واستخدمت طريقة القيود لتحويل الأهداف المختلفة لهدف واحد. كما استخدمت طريقتان لدراسة درجة الثقة في سلامة البيانات. الطريقة الأولى تعتمد على حل المشكلة لمجموعة من الخزانات الساحلية (والتي لها نفس الخصائص الإحصائية) معا. أما الطريقة الثانية تعتمد على تحليل النتائج المستنتجة من الحل الفردي لمجموعة مفترضة من الخزانات (طريقة مونت كارلو). استعملت الطريقة الخوارزمية الجينية للوصول لأمثل حل. وقد تم تطوير برنامج فورتران للحاسب الآلي لحل مثال افتراضي.

ABSTRACT

Most optimization models for management of coastal aquifers have ignored the effects of uncertainty due to spatial variability of hydraulic conductivity. This research explicitly incorporates uncertainty, in the hydraulic properties of coastal aquifer, into a procedure for optimal management of multi objectives. The sharp interface philosophy is adopted to simulate dynamics of the freshwater flow. Finite Element Method (FEM) was applied on the linear formulation of Strack to simulate the hydraulic response of the studied aquifer under different suggested rates of pumping. The LU-decomposition method was exploited to inverse the conductance matrix, that significantly decreases the computation time. The constraint technique was applied to simplify, without any relaxation, the multi objective management problem to single objective management problem. Genetic Algorithm (GA) was used to solve the nonlinear optimization problem. Two approaches were used to incorporate uncertainties of the hydraulic conductivity field through the management process. The first one solved the problem for multi realizations of hydraulic conductivity simultaneously. Then the post-optimality Monte Carlo (MC) analysis was performed to assess the reliability of the optimal solution. While the second approach applied the MC simulation method to the studied problem. A Fortran program was developed to apply the present methodology on a hypothetical coastal unconfined aquifer.

Key Words: *Coastal Aquifer- Strack's Formulation- Multiple Objectives Management- Uncertainty- Monte Carlo- Multiple Realization- Constraint Method.*

1-INTRODUCTION

Saltwater intrusion management problems are usually multi-objective. One of the most difficult problems associated with the simulation-optimization approach to coastal aquifers management is incorporating effect of

Accepted December 13, 2004.

the sharp interface modeling uncertainty into the optimal decision making process. Most coastal aquifers management strategies have been assumed to be deterministic, that the model used to simulate the aquifer is assumed to be without error [1, 2].

Precise field measurement for different variations of hydraulic conductivities through any studied aquifer is impossible subject. Actually, only the expertise insight of the hydrologist and/or a limited field measurements can be used to estimate approximate relations that can represent the unknown hydraulic conductivity field. Due to errors associated with field measurements and lack of data, the hydraulic conductivity field is always represented as a random field. That means the input data (hydraulic conductivities) through the studied domain are random variables, consequently the obtained output responses are also random variables.

To date, the literature dealing with saltwater intrusion management models under uncertainty is unavailable, whereas that dealing with groundwater management models under uncertainty is available in several papers. Wagner [3], applied the first-order first and second moment analysis to transfer uncertainty of the hydraulic conductivity to the management problem concerned with groundwater remediation. Also, he applied the chance constrained method to determine best strategy for management under a pre-specified degree in reliability. This scheme, till date, is never used within the literature concerned with management of coastal aquifer. The same work was repeated with Sawyer [4], but with unknown coordinates of the well locations. Angulo [5], used a utility criterion (weighted sum approach) in terms of construction, monitoring, and remediation to multi objective management of groundwater recovery. The drawback of his scheme is the necessity to know in advance the preference of each objective with respect to the others. Aly [6], used the artificial neural network (ANN) to simulate the hydraulic response for the contaminated aquifer due to different stresses, and applied GA to find the optimal remediation strategy. Fortunately the LU-decomposition can be exploited in the present work, that is even superior to the ANN from the accuracy point of view.

Bakr [7], studied management for groundwater remediation process under uncertainties of hydraulic conductivities, that concluded from the measured head and concentration data. This was achieved through the simultaneous indirect inverse for the simulation models of both the groundwater flow and the dispersion of pollution problems. He concluded that increasing the total pumping rate would increase the reliability of the aquifer remediation.

In this research the multi-objective management schemes that based on: 1) the maximization of the pumping rate of freshwater, 2) the minimization of land subsidence due to excessive pumping (equivalent to minimization the drop in water table level), and 3) the minimization of destructive land at sea side due to saltwater intrusion (equivalent to minimization of intruded volume of saltwater within the aquifer), were studied under uncertainty of the hydraulic conductivity field. In this work, log-hydraulic conductivity was assumed as a random field and represented with uncorrelated Gaussian normal distribution field. That multi objectives, nonlinear, stochastic, optimization problem of coastal aquifer is proposed for the first time in the literature.

The sharp interface approach [8] was adopted to simulate the dynamics of the steady flow within the freshwater zone in case of static/stagnant saltwater. Strack's linear formulation [9, 10] of the potential function was used instead of the nonlinear flow equation that adopts the piezometric head of the flow as a dependent variable [8]. This linear formulation simplified the solution process without any need for toe tracking. Also, it facilitated exploiting the LU-decomposition method [11] to inverse the conductance matrix once and using its inversion many of times during the optimization process, that made the computation time viable.

Genetic algorithm method in combination with the constraint method were used to optimize different conflicting non-commensurable objectives adopted in this work and obtaining their Pareto frontier. This stochastic optimization method is superior to any gradient method.

Two management model formulations are presented here. These formulations were suggested previously by Wagner [12] to study the reliability in optimal ground water remediation. The first, termed the multiple realization management model, simultaneously solves the nonlinear simulation-optimization problem for a sampling of hydraulic conductivity realizations. The second model, termed the Monte Carlo (MC) management model, solves the nonlinear simulation- optimization problem individually for a sampling of hydraulic conductivity realizations. These two methods provide a relationship between maximum pumping rate and reliability for pre-specified magnitudes of the other two objectives.

2-STRACK'S FORMULATION

Strack linearized, without any relaxation, the nonlinear flow equation that utilizing the piezometric head of the freshwater as a dependent variable. Instead he adopted the potential function ϕ as the dependent variable. Thus for static saltwater, the freshwater flow can be represented as, [9, 10]:

$$\frac{\partial}{\partial x}\left(K\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial \phi}{\partial y}\right)+ \sum_{i=1}^{nw}\delta(x-x_i)Q_i\delta(y-y_i)=0 \quad (1)$$

where, ϕ is the potential function (L^2), K is the hydraulic conductivity (L/T), x *and* y are rectangular coordinates (L), Q_i is pumping or recharging rate at well i (L^3/T), $\delta(z)$ is Dirac delta equal to 1 if z is zero otherwise equal to 0.0, and nw is number of wells through the studied domain. Figure 1 shows the vertical cross-section of unconfined aquifer. Distinction has been made between two zones, a freshwater zone (*zone I*) and a freshwater-saltwater zone (*zone II*). Strack demonstrated that ϕ is continuous across the two zones, and can be defined as (for unconfined aquifers), [9]:

$$\phi=\frac{1}{2}\left[h^2-(\rho_s/\rho_f)d^2\right] \textit{ for zone I} \quad (2)$$

$$\phi=\frac{\rho_s}{2(\rho_s-\rho_f)}[h-d]^2 \textit{ for zone II} \quad (3)$$

where, h is the water table head above the impervious bed of the aquifer (L), d is depth of sea water above the aquifer bed (L), and ρ_s, ρ_f are the saltwater and freshwater densities respectively (M/L^3). The two zones are separated at piezometric head h_{toe} equal to $(\rho_s/\rho_f)d$, consequently the potential ϕ_{toe} between the two zones should be, [9]:

$$\phi_{toe}=[\rho_s/\rho_f].[(\rho_s-\rho_f)/2\rho_f].d^2 \quad (4)$$

The following boundary conditions were used in this research, Fig. 2:

$$\partial\phi/\partial n = 0.0 \quad on\ sides\ AD,\ CB \qquad (5)$$

$$\phi = \frac{(\rho_s - \rho_f)S^2}{2\rho_s}\ on\ side\ AB \qquad (6)$$

$$\partial\phi/\partial n = qu/K \quad on\ side\ DC \qquad (7)$$

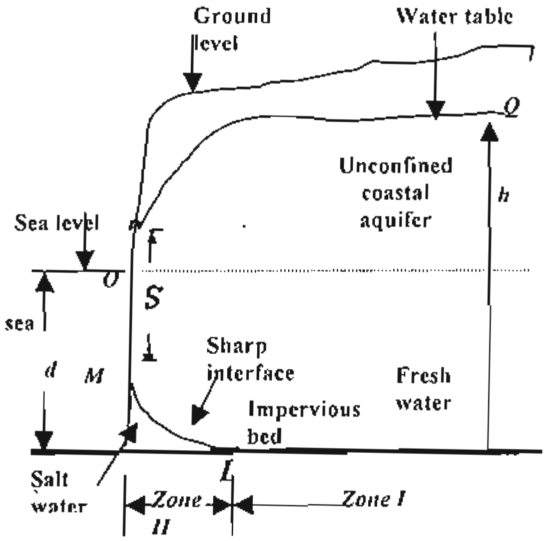

Figure 1. Vertical cross-section of unconfined coastal aquifer.

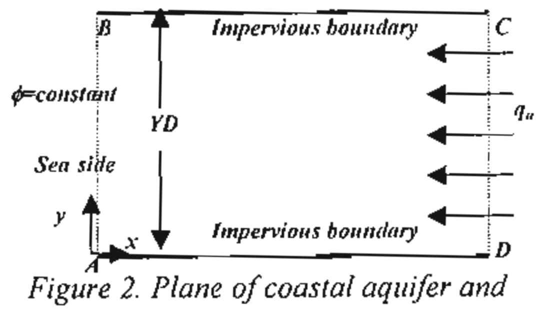

Figure 2. Plane of coastal aquifer and boundary conditions.

where, q_u is rate of water enters the aquifer per unit width (L^2/T), S represents seepage face height at sea side (L), that is equal to MP, Figure 1. Seepage face height can be assumed from Glover's analytical solution as, [10]:

$S=(Q_{net}/YD)/(K.\{\rho_s-\rho_f\}/\rho_s)$ (8)

where, Q_{net} is net freshwater recharges out the aquifer at the sea side (L^3/T), YD is total length of the sea boundary (L), and K is assumed equal to average hydraulic conductivity along the sea side for heterogeneous aquifers (L/T).

Finite element method (FEM) [13, 14] was used to solve eq. 1 for different vectors of pumping rates from the existing well system. In this research linearity of Strack's formulation was exploited by inversing the conductance/ stiffness matrix once and using its inversion numerous times through the optimization process. It must be noticed that there is a conductance matrix corresponding to every realization from the hydraulic conductivity random field.

3-CONSTRAINT METHOD

The solutions of a multi objective problem are referred to in the literature as non-inferior, efficient, Pareto-optimal, and non-dominated. Solving a multi objective optimization problem entails finding a set of non-inferior solutions.

If the decision variables are represented by the vector Q_w, and the multi objectives by Z_1 to Z_n, where n is the number of objectives. Then, a solution of a multi objective optimization problem, Q_w', is said to be non-inferior if there exists no other feasible solution Q_w belongs to the decision space such that $Z_i(Q_w) \leq Z_i(Q_w')$ *for all* $i=1,2,..,n$, (in case of minimization problem) with strict inequality for at least one objective. In the present work different multi objectives are conflicting functions. To generate the trade off surface between these objectives a technique for the generation of non-inferior solutions is required. The technique selected in this paper is the constraint method. It operates by optimizing one objective function while all other objectives are constrained to some feasible values [15].

The main drawback of the constraint method is the necessity of solving the optimization problem iteratively for every selected constraint. Therefore, computation time increases exponentially with number of objectives. GA was selected to find optimal solution of the present problem. In contrast to any gradient optimization method, this stochastic optimization method can easily handle different objectives simultaneously. That means it can produce multiple non-inferior solutions from solving only one optimization problem.

Cieniawski [16], used different forms of GA to solve two objectives for groundwater monitoring problem. He applied: 1) Pareto optimal ranking formulation, 2) vector-evaluated GA formulation and 3) combination of the above the two formulations (1 and 2), to handle his problem. Cieniawski reported that none of the suggested GA formulations had the ability to generate the entire trade-off curve in a single iteration. These GA formulations search in random directions, consequently non-uniform set of non-inferior solutions are always obtained. In the present problem constant and uniform set for the non-inferior solutions must be determined to facilitate determining probability/ reliability associated with each non-inferior solution. Hence, simple GA formulation that can be adopted for only single objective function will be used through this work. GA is used to find non-inferior/optimal solution corresponding to optimal solution of one objective function (maximum pumping rates) that was restricted with a pre-specified feasible values for the other two objectives functions. Hence, that scheme can produce a uniform distribution of the non-inferior solutions, that facilitate determination of reliability without any interpolation error.

4-MULTIPLE REALIZATION MODEL

This stochastic model [12], is a nonlinear simulation- optimization problem in which numerous realizations of the random hydraulic conductivity field are considered simultaneously. The mathematical formulation of the multiple realization model within the constraints method is:

$$maximize[Z_1(Q_w)] \qquad (9)$$

Subjected to the following constraints:

$$Q_{i\text{-}lower} \leq Q_i \leq Q_{i\text{-}upper} \qquad i=1,2,\ldots,nw \qquad (10)$$

and,

$$\min Z_2(\mathbf{Q}_w, \mathbf{K}_n)_n \geq D_2, \quad Z_3(\mathbf{Q}_w, \mathbf{K}_n)_n \leq D_3 \qquad for\ n=1,2,\ldots,NR \qquad (11)$$

where, min means minimum, $Z_1(\,)$ is the objective function that represents total extracted freshwater divided by the constant magnitude of freshwater enters the aquifer , $Z_2(\,)_n$ objective function represents height of water table level above mean sea level at the upstream side of the studied aquifer for realization n (upstream nodes of the Finite element mesh were used as control points) (m), $Z_3(\,)_n$ third objective function that represents intruded volume of seawater within the aquifer at realization n (*million* m^3), nw is number of wells through the studied domain (number of decision variables), $\mathbf{Q}_w$ is a vector of nw decision variables (rate of pumping from every well), and Q_i, $Q_{i\text{-}lower}$, $Q_{i\text{-}upper}$ are rates of pumping from well i and its lower and upper limits respectively, $\mathbf{K}_n$ is a vector of different hydraulic conductivities associated within different elements at realization n, NR is number of hydraulic conductivity realizations and D_2, D_3 are the pre-specified feasible constraints subjected to objective functions 2 and 3 respectively. By solving eqs. 9-11 iteratively for feasible magnitudes of D_2 and D_3 their nondominate solutions can be obtained through the GA.

Once the hydraulic conductivity realizations are generated the nonlinear optimization problem is solved for the *NR* realizations simultaneously. Therefore the constraints, Eqs. 10 and 11, must be satisfied for every realization. It is as if a single pumping strategy is designed to be successful for each of the *NR* different aquifers (realizations).

For a thorough investigation of the effects of uncertainty due to spatial variability of the hydraulic conductivity, the multiple realization management model would have to be performed using a large number of hydraulic conductivity realizations. Number of multiple realizations was restricted to 20 in this work. With this limitation, it can not assumed the optimal management strategy is feasible for all possible conductivity realizations. Therefore, a post-optimality MC analysis is performed to assess reliability of the non-dominant/optimal solutions. That means the non-dominant solutions must be checked against another conductivity realizations to estimate the reliability degree corresponding to these solutions.

5-MONTE CARLO MODEL

This second stochastic model solves a series of individual optimization problems, each with a single realization of hydraulic conductivity. Therefore, if there are *NM* hydraulic conductivity realizations, the MC simulation model will provide *NM* optimal Pareto frontiers. For deterministic optimal solution of one conductivity realization the following equations must be solved:

$$maximize[Z_1(Q_w)] \tag{12}$$

Subjected to the following constraints:

$$Q_{i\text{-}lower} \leq Q_i \leq Q_{i\text{-}upper} \quad i=1,2,\ldots,nw \tag{13}$$

and,

$$\min Z_2(Q_w) \geq D_2,$$
$$Z_3(Q_w) \leq D_3 \tag{14}$$

Equations 12 to 14, must be resolved for *NM* realizations. Uncertainty of the hydraulic conductivity field would produce different Pareto frontiers, one for every conductivity realizations. Each of the *NM* deterministic Pareto frontiers obtained from the MC deterministic management model represents a random sampling from the probability distribution function (pdf) of the uncertain/random Pareto frontier.

Any output variable V can be represented through normal distribution as suggested by the central limit theorem [17]. Then the mean and the standard deviation of that variable can be concluded as, [18]:

$$\mu_v = \frac{1}{NM}\sum_{k=1}^{NM} V_k \tag{15}$$

$$\sigma_V^2 = \frac{1}{NM-1}\sum_{k=1}^{NM}\{V_k - \mu_V\}^2 \tag{16}$$

where, μ_v and σ_V^2 are the mean and the standard deviation of output variable V.

6-GENETIC ALGORITHM

This technique is a search method that uses the mechanisms of natural selection to search through decision space to optimal solutions. GA has shown to be valuable tool for solving complex optimization problems in a broad spectrum of fields. The GA-based solution method can generate both convex and non-convex points of the trade-off surface, and accommodate non-linearities within the multiple objective functions. GA consists of three basic operations [19]: 1) selection, 2) crossover (mating), and 3) mutation. In using GA, several vectors, or strings which represent different decision sets are formed randomly. These strings are evaluated on their performance or fitness with respect to some objective functions. The following objective function F is used in this work:

$$F=\sum_{r=1}^{NR}\left\{\sum_{w=1}^{nw}\left[Q_w-p_1.H_w\right]-\sum_{c=1}^{nc}p_2.H_c-p_3.H\right\} \quad (17)$$

where, p_1, p_2, and p_3 are different penalties respectively corresponding to 1) violation of saltwater at well w, 2) decreasing height of water table level above mean sea level at control node c than the pre-specified constraint D_2 and 3) increasing the intruded volume of sea water within the aquifer than D_3, H_j is the Heaviside unit step function that equal to one only when violation exists at j otherwise diminishes to zero, and nc are number of control nodes at the upstream side of the aquifer. It must be noticed that the above function is straightforward applicable to the multi realization model. In case of MC model only one conductivity realization must be solved every time, so the NR in eq.17 must be replace with one.

Abdel-Gawad [20], studied behaviors of different forms of genetic algorithms, on the convergence rate towards the final optimum. He concluded that best formulation composed from: real coding, uniform crossover, modified mutation, constant value of penalty. That formulation of GA was adopted within the present research. The tournament strategy was applied for both of replacement and reproduction process.

7-STEPS OF SOLUTION

A Fortran program that was previously written to handle deterministic multi objective management problem is modified to incorporate the reliability effect. For the multiple realization stochastic model the following main steps were applied:

1) Generate NR realizations of the hydraulic conductivity field.
2) Calculate the conductance matrix corresponding to every realization and inverse it with the LU decomposition method [11]. Store the NR inverted matrices for subsequent calls.
3) Apply GA for all realizations simultaneously to find non-inferior solution corresponding to the pre-assumed feasible magnitudes of the constraints D_2 and D_3. During the optimization process only load vector corresponding to different pumping rates are changed, the analogy hydraulic responses for different realizations can be easily calculated by only multiplying the inverted matrices with non-zero rates of pumping.
4) Repeat step 3 several times for different feasible magnitudes of the constraints D_2 and D_3. This process generates the trade-off surface between different objectives (Pareto frontier).

The MC model used the same previous steps with minor modifications:

a) Replace NR with 1.
b) Repeat steps 1 to 4, NM times, one for every conductivity realization.
c) Determine the mean and standard deviation for every output variable.

Different realizations generated with the MC model were used to test the post-optimality of the multiple realization solution.

8-HYPOTHETICAL AQUIFER

Coastal unconfined aquifer similar to that shown in figure 2, is suggested in this paper. The aquifer is *5500m* parallel to the sea (y-direction) and with *4000m* perpendicular to the sea (x-direction). The depth of the aquifer below mean sea level is taken equal to *15m*. The aquifer has no flow boundary at the *BC* and *AD* sides. The sea boundary *AB* is controlled by Dirichlet boundary condition at the sea side, Eq. 6. The east boundary *CD* has constant uniform discharge of groundwater flow $q_u=1.0 m^3/day/m$. The logarithm of hydraulic conductivity random filed is assumed as a normal distribution with mean $\mu_Y = 2.0$, and standard deviation $SY= \sigma_Y = 1.0,\ 1.5,\ 2.0$. The following data are assumed through the present study: $nw = 15$, $\rho_s = 1.025\ g/cm^3$, $\rho_f = 1.0\ g/cm^3$. Table 1, contains different data about coordinates and upper and lower limits of pumping rates (decision variables) for the existing well system.

Table 1, Cartesian coordinates, pumping rates limits for the well system.

Well No.	X- (m)	Y- (m)	Lower Limit of Pumping (m^3/day)	Upper Limit of Pumping (m^3/day)
1	1000	5500	150	600
2	1700	4100	150	1300
3	1500	3850	150	1100
4	1200	3400	150	800
5	1700	3200	150	1300
6	1800	2700	150	1400
7	3500	2500	150	1500
8	1600	2200	150	1200
9	1600	1800	150	1200
10	1500	1400	150	1100
11	2000	1000	150	1500
12	1000	800	150	600
13	1600	500	150	1200
14	3600	200	150	1500
15	1400	0	150	1000

The aquifer is discretized into *250m X 250m* finite elements, with hydraulic conductivity constant within each cell. Quadrilateral elements with 4-nodes were used to simulate the aquifer. Therefore the continuously varying hydraulic conductivity field was represented by 352 discrete hydraulic conductivity zones. The resulting finite element model had 391 nodes and 352 elements.

The following data were used with genetic algorithm: *number of individuals= 100, number of generations = 50, crossover ratio=0.75, mutation ratio=0.15, seed number = -10, probability of switching off any well=0.3,* p_1= *2000*m^3 */day / intruded well,* p_2= *500* m^3 */day/upstream node,* p_3= *10000* m^3 */day/realization,*

9-RESULTS AND DISCUSSION

The previous hypothetical aquifer was analyzed here with both the multi realization method and the MC method. Three objective functions were considered during the management process: 1) objective function (*Z1*) represents ratio of maximum pumping rate of freshwater from the aquifer (total pumping rate divided by total freshwater enters the aquifer), 2) objective function (*Z2*) is the minimum height of the water table level above mean sea level at upstream side of the aquifer (*m*), 3) objective function (*Z3*) is volume of intruded saltwater within the aquifer in *million of cubic meters*.

The constraint method was adopted to simplify the problem to one objective only. So, all objective functions except one must be pre-specified at feasible values. To obtain feasible ranges of different constraints the deterministic problem must be solved first for one or two conductivity realizations. From the calculated Pareto frontiers, reasonable assumptions for the feasible ranges can be considered.

The feasible range for the height of the water table level above mean sea level at upstream side of the aquifer is taken *5 m to 17 m*. While, feasible range of intruded volume of salt water through the aquifer is taken *11 million m^3 to 18 million m^3*. The Pareto frontier is specified at different combination of the following constraints: D_2= *5, 7, 9, 11, 13, 15, 17m,* and D_3=*11, 12, 13, 14, 15,16, 17, 18 million m^3*. That means for every Pareto frontier 56 non-dominated uniformly distributed solutions was used.

Figure (3a-g), show results of the multiple realizations method for maximum ratio of extracted freshwater *Z1* against the other two objective functions *Z2* and *Z3*. The problem is solved for number of conductivity realizations *NR* equal to *10* and number of generations within the genetic algorithm *NG* equals *50*, the standard deviation for the logarithm of the hydraulic conductivity $SY = \sigma_Y$ are taken equal to 1.0, 1.5, 2.0 at Figures (3-a, 3-c) and (3-e) respectively. The same parameters are restudied in Fig. (3-b, 3-d, 3-f) but for number of conductivity realizations *NR* equal to 20. To study the effect of number of generations adopted by the GA method on final solutions two runs were carried out for simulations which have $SY = \sigma_Y = 2.0$ with number of generations *NG* equal to *100* instead of *50*, Fig. (3-g and 3-h).

From different Pareto frontiers in figure (3a- 3h), the following notes can be recognized: 1) increasing both *NR* and *SY* decrease optimal magnitudes of objective function *Z1*, but *SY* has a pronounced effect than *NR* , 2) increasing number of generation from *50* to *100* has a minor effect on Pareto frontiers. Due to the stochastic behavior of the GA method, non-dominated solutions have little enhancements at some locations and became bad at other ones, 3) for all runs height of water table level above mean sea level controls the management results for feasible range of *Z2* from *17m to 13 m,* for lesser magnitudes of *Z2* both of the two objectives *Z2* and *Z3* have an effect on different Pareto frontiers.

A post-optimality Monte Carlo analysis is performed to assess reliability of different Pareto frontiers shown in figure (3a- 3h). In this MC analysis one hundred conductivity realization were generated. For each realization the different decisions variables, calculated from the multiple realization method at different non-dominant solutions, were applied. The reliability (at different uniformly distributed non- dominant solutions) was then calculated by determining the percentage of realizations for which there were no pumping of salt water at well locations.

Figure (4a- 4h), shows different reliabilities corresponding to various runs presented in figure (3a- 3h). It can be noticed that increasing both magnitudes of standard deviation of logarithm of the hydraulic conductivity (*SY*) and height of water table level above mean sea level (*Z2*) increase significantly the reliability level. Increasing number of realizations *NR* form *10* to *20* or increasing number of generations *NG* from *50* to *100*, has a minor effect on the estimated reliability.

Results of the MC method are shown in figure (5a- 5h), with the same parameters adopted in figure (3a- 3h). One hundred conductivity realizations were considered and solved individually. Mean and standard deviations at different non-dominant solutions were calculated using Eqs. (15 and 16). From figure (5-a, 5-c, and 5-e) the ensemble mean of different realizations decreases as *SY* increases. The mean values are mainly dependent on objective function *Z2* for magnitudes between *17m* and *14m*. As *Z2* increases its effect on *Z1* decreases. For values of *Z2* less than *8m* only objective function *Z3* control the non-dominant solutions. Figure (5-b, 5-d, and 5- f) shows that standard deviation of objective function *Z1* increases as both *Z2* and *SY* increases. As *SY* decreases from 2.0 to 1.0 the effect of objective function Z3 on the standard deviation of objective function *Z1* diminishes. Also, it can be noticed that increasing the number of generations *NG* from *50* to *100* has a minor effect on the results, Fig. (5e- 5h).

As a consequence of the MC simulation the required number for simulating the aquifer with the FEM is = non-dominant solutions(56) X number of conductivity realizations(100) X number of strings(100) X number generations(50 or 100) = (28 or 56) million simulations. To simulate the desired aquifer millions of times with the FEM, a computation time for several days will be required. Using the LU decomposition method decreases significantly the computation time to only several hours. Unfortunately, that method is limited only to linear problems which corresponding to single aquifer, confined or unconfined, with impervious straight beds.

10-CONCLUSIONS AND RECOMMENDATIONS

Within this work, two formulations of multi objective management for coastal aquifer under uncertainty of hydraulic conductivities were examined for the first time in the literature. The first of these formulations, named the multiple realization method, which provides reliable design by simultaneously solving the nonlinear simulation-optimization problem for a representative sample of conductivity realizations. The optimal design strategy is feasible for all realizations included in the multi realization model. MC analysis shows that design strategies based on as few as 10 conductivity realizations have reliability ranges form 1 to 0.7 for the non-dominant solutions. Only at limited solutions the reliability reduces to 0.5. Increasing number of realization from *10* to *20* has a minor improvement on the reliability level.

The second formulation, named the MC method, solved the nonlinear simulation- optimization problem individually for *100* conductivity realizations. This method provides *100* deterministic realizations of Pareto frontiers which were used to estimate the mean and the standard deviations at different non-dominant solutions. Results of the MC model showed that, as *SY* increases the standard deviation of maximum pumping rates increases and the mean of pumping rates decreases. Optimal solutions obtained from the multi realization approach always less than mean pumping rate corresponding to the MC approach.

In this paper unconditional random log-hydraulic conductivity fields were generated to represent different conductivity realizations of the studied domain. Unconditional hydraulic conductivity field implies that no data is available to condition on. Such a situation could occur in practice when no measurements are available but more general information about an aquifer justifies a guess of the spatial statistical parameters of its hydraulic conductivity variation. Another possibility is the availability of measurements outside the area of interest, but close enough to be representative of its heterogeneous structure. Hoeksema [21] studied 31 aquifers in USA and concluded that Y (logarithm of hydraulic conductivity) can be simulated with dependent correlated exponential covariance models. So, it is recommended to examine effect of uncertainty of different controllable coefficients within these models. Also, it is recommended to study conditional simulation using information, from various bore loggings, pumping tests and tracer tests, to reduce the uncertainty of the generated conductivity realizations.

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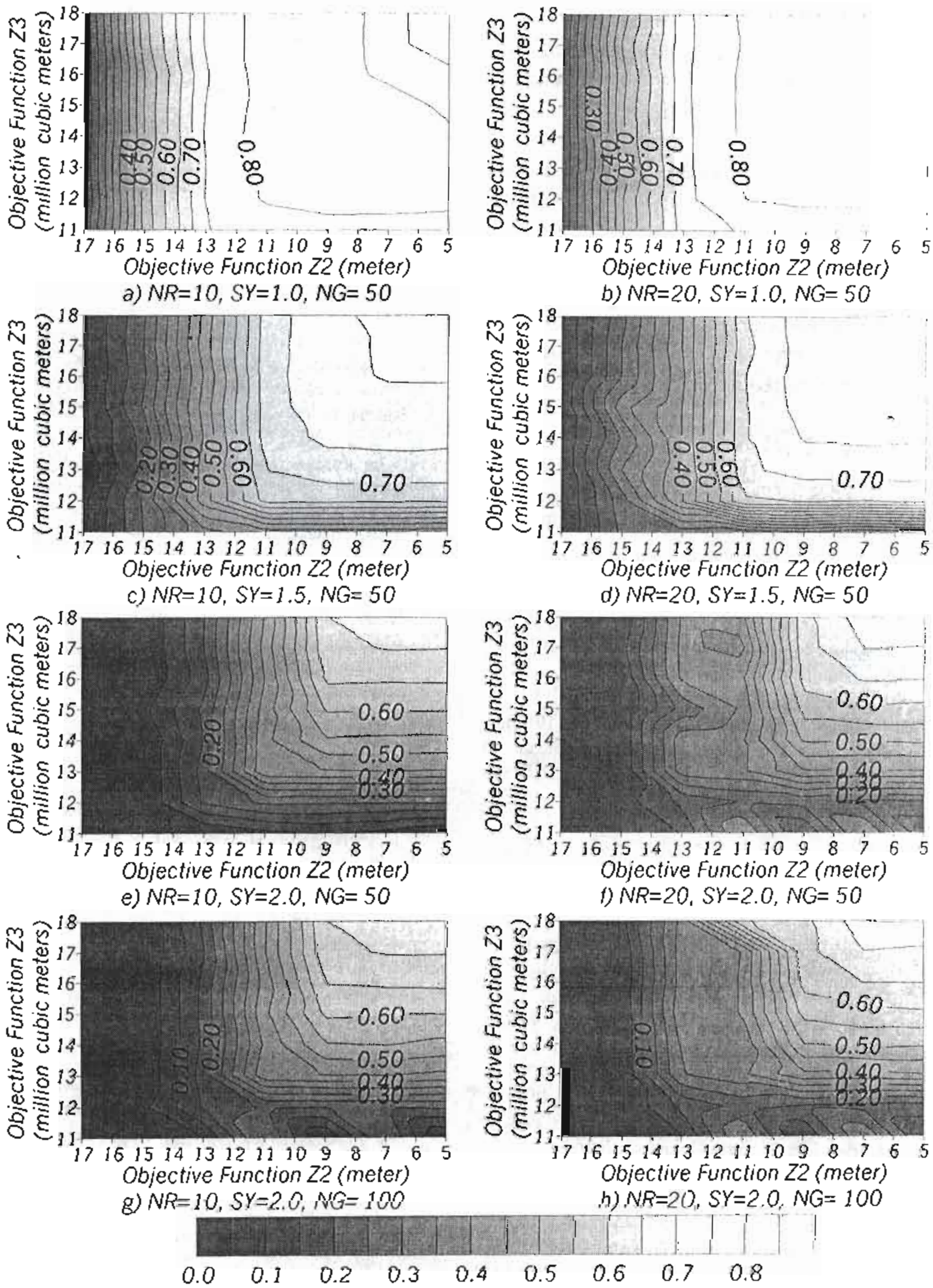

Figure. 3 Optimal magnitudes of objective function Z1 against Z2 and Z3, estimated from the Multi realization approach. (NR= number of conductivity realizations, SY= σ_Y = standard deviation for the logarithm of the hydraulic conductivity, NG= number of generations in GA).

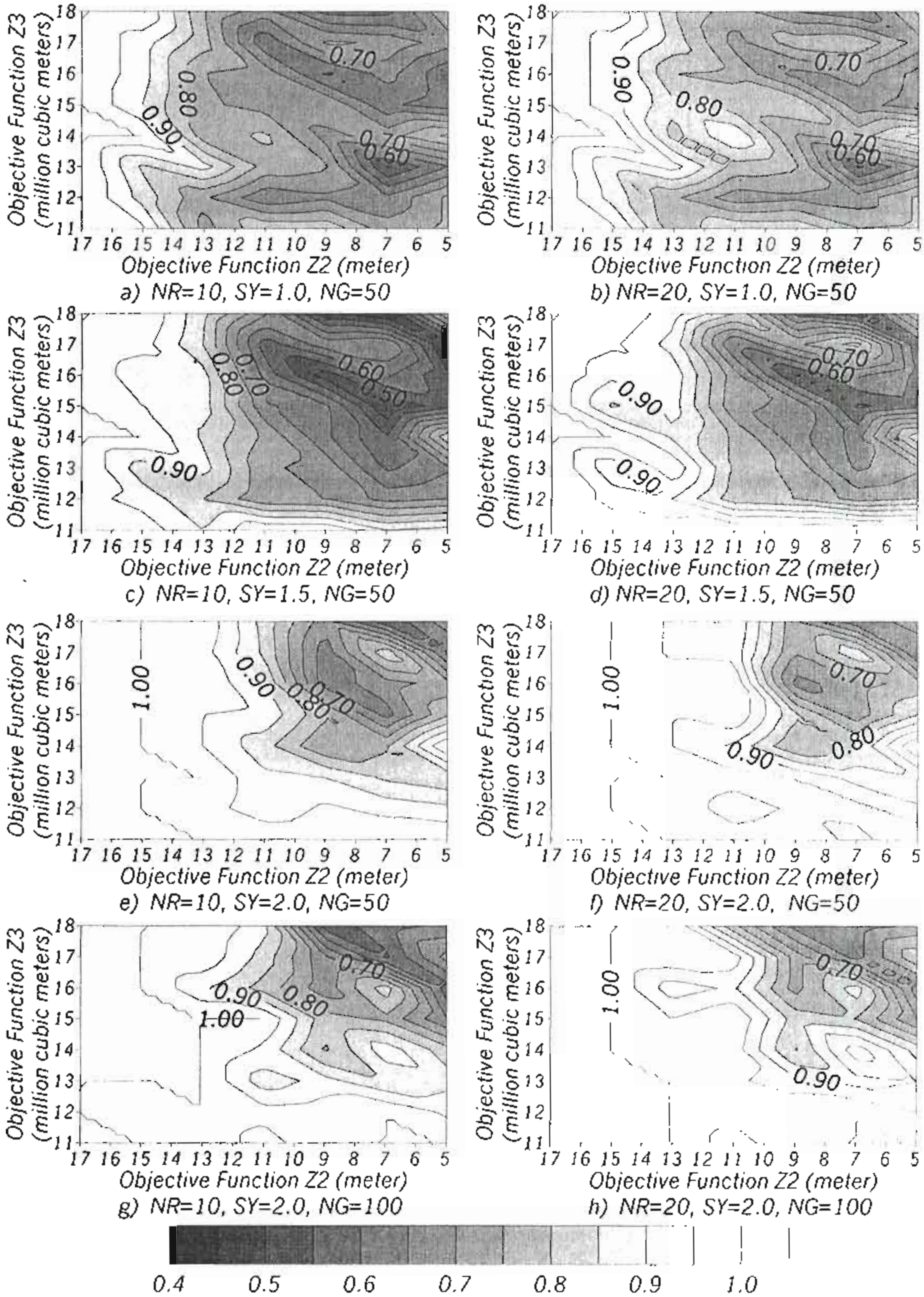

Figure. 4 Reliability of objective functions Z1, shown in figs. 3-a-h, obtained from the post-optimality of 100 conductivity realizations . (NR= number of conductivity realizations, SY= σ_Y = standard deviation for the logarithm of the hydraulic conductivity, NG = number of generations in GA).

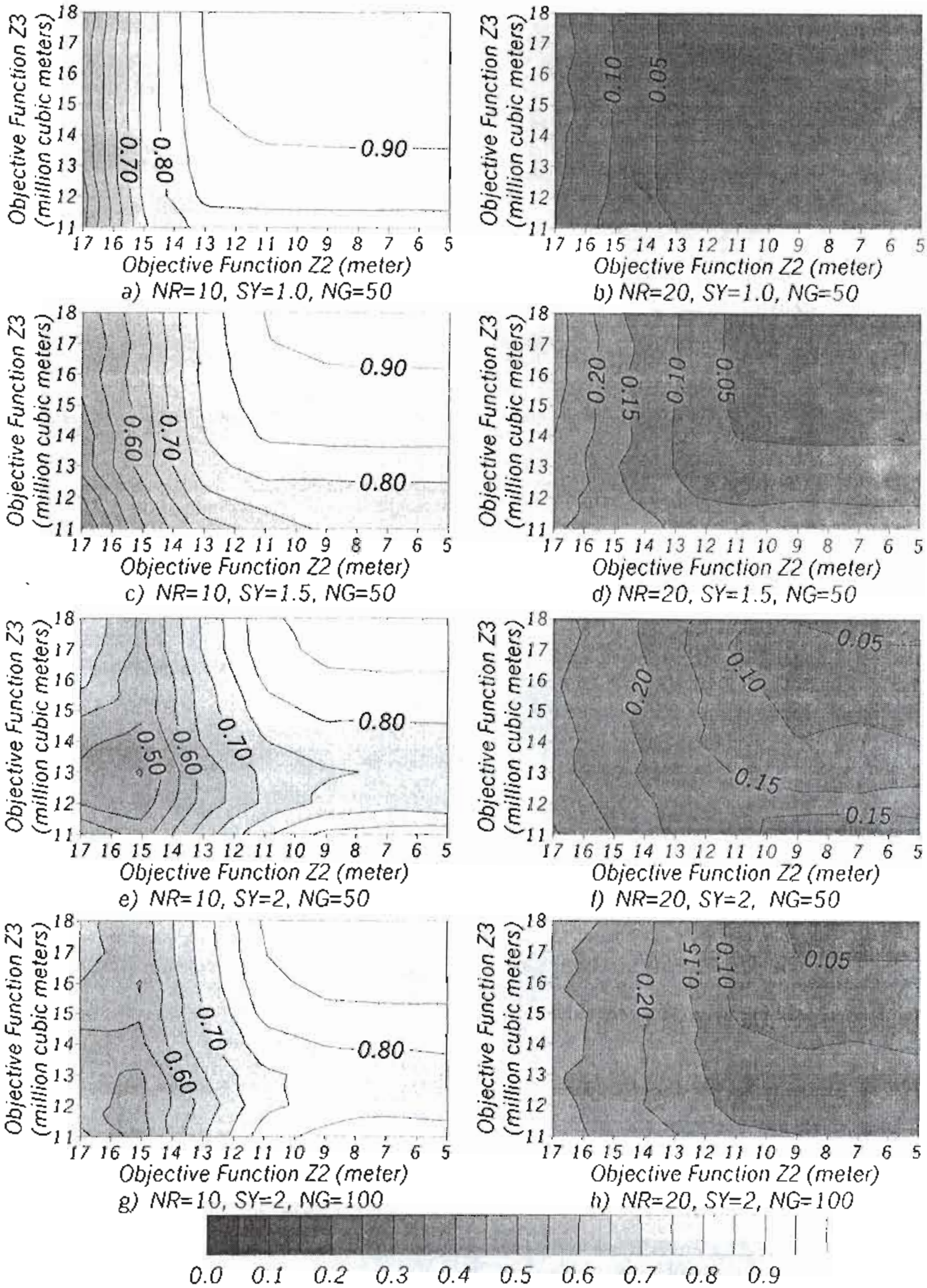

Figure. 5 Mean of objective function Z1 (a, c, e, g) and its standard deviation (b, d, f, h) due to 100 MC simulations. Results drawn against objective functions Z2 and Z3. (NR= number of conductivity realizations, SY= σ_Y = standard deviation for the logarithm of the hydraulic conductivity, NG= number of generations in GA).