MANAGEMENT OF SOUTH CHENNAI COASTAL AQUIFER SYSTEM - A MULTI OBJECTIVE APPROACH

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ABSTRACT *Many coastal areas in the world are dependent on local fresh groundwater resources because of heavy urbanization. Due to constant pumping and improper management, the South Chennai aquifer is facing a severe threat of being contaminated by seawater. In order to study the extent of seawater intrusion, the parameter $Cl/(HCO_3+CO_3)$ is taken as a solute and the indicator of seawater intrusion and analyzed through SEAWAT. Model calibration has been carried out using the data pertaining to the period 1990-2002. Model prediction has been done upto the year 2010 with management strategies such as modernizing existing tanks, construction of a semi pervious barrier and optimization of pumping quantities. Management of seawater intrusion is a multi objective decision problem. The problem has been formulated as a multi objective optimization problem consisting of two objectives such as maximization of pumping and minimization of total cost of desalination considering the constraints on water levels and pumping. Multi objective interactions between the various trade-offs have been analysed using multi objective evolutionary algorithm.*

Key words South Chennai coastal aquifer; water management; multi objective decision problem; optimization.

INTRODUCTION

Many coastal areas in the world are dependent on local fresh groundwater resources because of heavy urbanization. One of the most important threats to groundwater in coastal areas is seawater intrusion. In recent decades, the coastal aquifers have assumed greater importance because of increased demands placed on groundwater to meet the growing needs of water in a large urban area like Chennai City. The South Chennai aquifer that holds substantial quantity of groundwater, meets 20% of city's water requirement. In drought years the groundwater resource is the sole safeguarding arrangement to meet the drinking water requirement. Due to constant pumping and improper management, this aquifer is facing a severe threat of being contaminated.

The South Chennai aquifer system covers the area between latitudes 12°05' N and 13°15' N and between longitudes 80°10'13" E and 80°16'30" E (Fig. 1). It covers an areal extent of about 200 km^2. The area is bounded by the Bay of Bengal on the eastern side while the western portion extends up to villages located near the old Mahabalipuram road, starting from Perungudi in the North to Kelambakkam in the South. The Adyar river confluences with the Bay of Bengal on the Northern

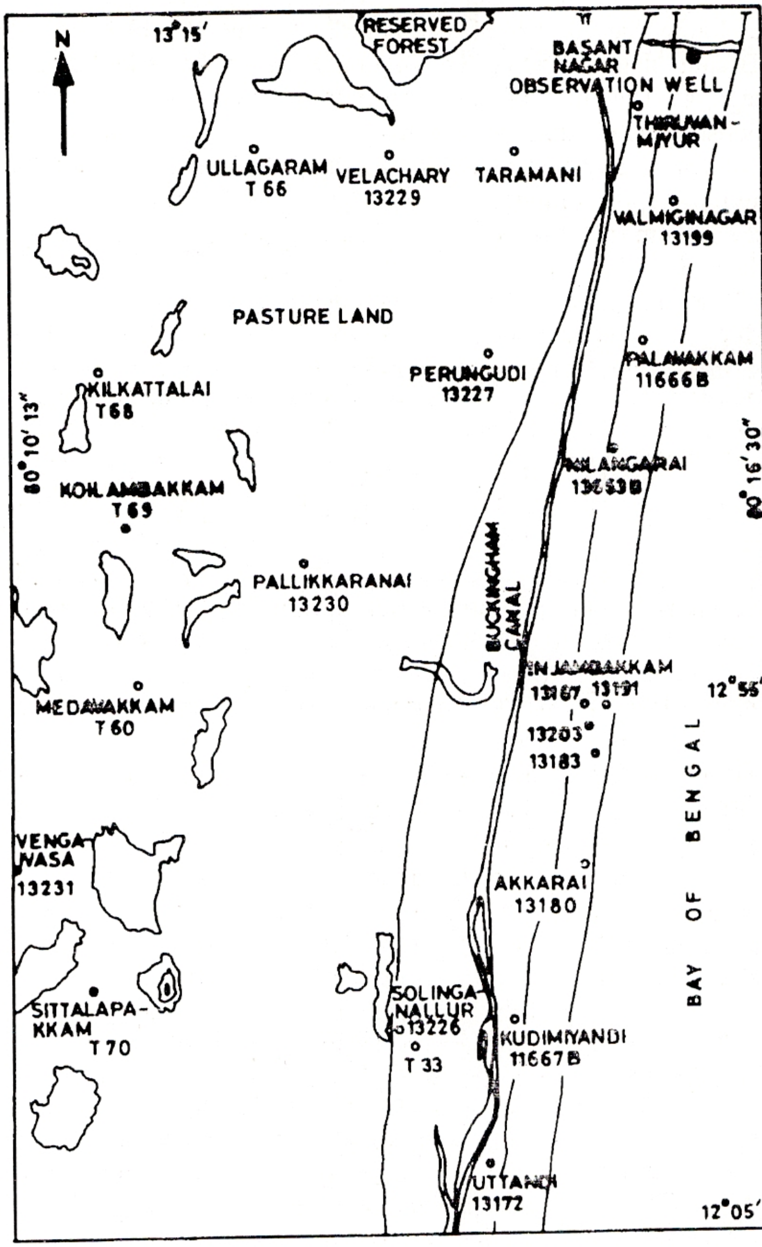


Fig. 1 Study area.

boundary of the area and the Southern side is bounded by the Kovalam creek. The Buckingham canal along the western margin runs almost parallel to the Bay of Bengal in the north-south direction and contains stagnant water. The study area has a terrain elevation ranging between 3 and 10 m and experiences a sub-tropical climate, the annual temperature ranging between 24°C and 41°C. The annual rainfall is about 1200 mm. The aquifer receives around 60% of its recharge from northeast monsoon during the months of October, November and December. From an earlier study it was found that 10-15% of the rainfall is getting recharged into the aquifer. Both the Besant Nagar and the Thiruvanmiyur-Kovalam belts comprise coastal alluvium deposits. The alluvium comprises of sand (medium to coarse grained), silt, clay and shells. Investigations, through drilling of boreholes in this area, carried out by the Groundwater Division of Public Works Department revealed that depth of coastal alluvium deposits ranges between 16.0 m and 22.0 m below ground level. The coastal alluvium is followed by basement of Charnockite of Archaean age.

The ARGUS ONE software with SEAWAT has been used for the development of numerical model. Chloride (Cl) is the dominant ion in coastal water and normally occurs in small amounts in groundwater. On the other hand, bicarbonate (HCO_3) is usually the most abundant ion in groundwater and occurs in small amounts in seawater. Thus, in order to study the extent of seawater intrusion, the parameter $Cl/(HCO_3+CO_3)$ is taken as a solute and the indicator of seawater intrusion. Model calibration was done by using the values of the period 1990-2002. For model calibration, conductivity and dispersivity were varied within reasonable limits. Model was validated for the year 2003. Model prediction was done up to the year 2010 with management strategies such as modernizing existing tanks, construction of a semi pervious barrier and optimization of pumping quantities. Multi objective optimization was used for the development of pumping strategies.

NUMERICAL MODEL DEVELOPMENT

There are mainly two general approaches used to analyze saltwater intrusion in coastal aquifers, the sharp interface approach (Essaid, 1990) and the disperse interface approach. The sharp interface approach is based on the simplification of the thin transition zone relative to the dimension of the aquifer. The freshwater and saltwater are considered to be two immiscible fluids of different constant densities. The studies based on this approach are modeled by only solving the groundwater flow equation. The disperse interface approach explicitly represents a transition zone that is a mixing zone of the freshwater and saltwater within an aquifer due to the effects of hydrodynamic dispersion. In the transition zone there is a gradual change in density. Models that incorporate simulation of the transition zone require simultaneous solution of the governing fluid flow and solute transport equations. The computer code that was used in the present study is SEAWAT (Guo and Langevin, 2002) which is based on disperse interface approach.

The governing equation for variable-density flow in terms of freshwater head as used in SEAWAT is:

$$\frac{\partial}{\partial \alpha}\left(\rho K_{f\alpha}\left[\frac{\partial h_f}{\partial \alpha}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \alpha}\right]\right)+\frac{\partial}{\partial \beta}\left(\rho K_{f\beta}\left[\frac{\partial h_f}{\partial \beta}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \beta}\right]\right)$$
$$+\frac{\partial}{\partial \gamma}\left(\rho K_{f\gamma}\left[\frac{\partial h_f}{\partial \gamma}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z}{\partial \gamma}\right]\right)=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}-\overline{\rho}q_s \qquad (1)$$

where $K_{f\alpha}, K_{f\beta}, K_{f\gamma}$ is freshwater hydraulic conductivity in α, β, and γ directions, respectively; C is solute concentration; θ is porosity; S_f is the specific storage in terms of freshwater head; $\overline{\rho}$ is the density of water entering from a source or leaving through a sink; q_s is the volumetric flow rate per unit volume of aquifer representing sources and sinks; h_f is the freshwater head; Z is the elevation of the point of measurement above some datum; ρ_f is the density of freshwater in the piezometers; ρ is the density of water in the formation at the point of velocity calculation; and t is time.

In addition to the flow equation (Eq.1), a second partial differential equation is required to describe solute transport in the aquifer. Solute mass is transported in porous media by the flow of groundwater (advection), molecular diffusion, and mechanical dispersion. The transport of solute mass in groundwater can be described by the following partial differential equation:

$$\frac{\partial C}{\partial t} = \nabla.(D.\nabla C) - \nabla.(vC) - \frac{q_s}{\theta} C_S + \sum_{k=1}^{N} R_k \tag{2}$$

where D is the hydrodynamic dispersion coefficient; v is the fluid velocity; C_s is the solute concentration of water entering from sources or sinks; and R_k (k = 1, ..., N) is the rate of solute production or decay in reaction k of N different reactions.

Groundwater flow causes the redistribution of solute concentration, and the redistribution of solute concentration alters the density field, thus, affecting groundwater movement. Therefore, the movement of groundwater and the transport of solutes in the aquifer are coupled processes, and the two equations must be solved jointly to obtain variable density flow. SEAWAT-2000 (Langevin *et al.*, 2003) is the latest release of the SEAWAT computer program for simulation of three-dimensional, variable-density, transient groundwater flow in porous media. SEAWAT-2000 was designed by combining a modified version of MODFLOW-2000 and MT3DMS into a single computer program. Argus ONE version 4.2w was used as a pre- and post-processor for the numerical model.

The study area of the aquifer is divided using a finite difference grid having grid cells of size 250 m × 250 m nearer to the coast and grid cells of size 500 m × 500 m in the remaining portion (Fig. 2). From the resistivity survey and borehole lithology, it is clear that the aquifer system is under unconfined condition. The hydraulic conductivity and specific yield of the aquifer between Buckingham and sea coast are taken as 60 m/day and 0.27, respectively, and between western boundary and Buckingham canal the values are taken as 35 m/day and 0.24, respectively. The aquifer is hydraulically connected to the Bay of Bengal in the east and Adyar river and Muttukkadu estuary along north and south, respectively. The southern side Muttukkadu estuary and eastern side Bay of Bengal are given as constant head boundaries at mean sea level (msl). The western side is far from the study area and is constant head boundary according to past hydraulic head values. Similarly the boundary condition for the solute transport model is constant concentration at the sea side while a concentration equal to that of freshwater is assumed at the western boundary.

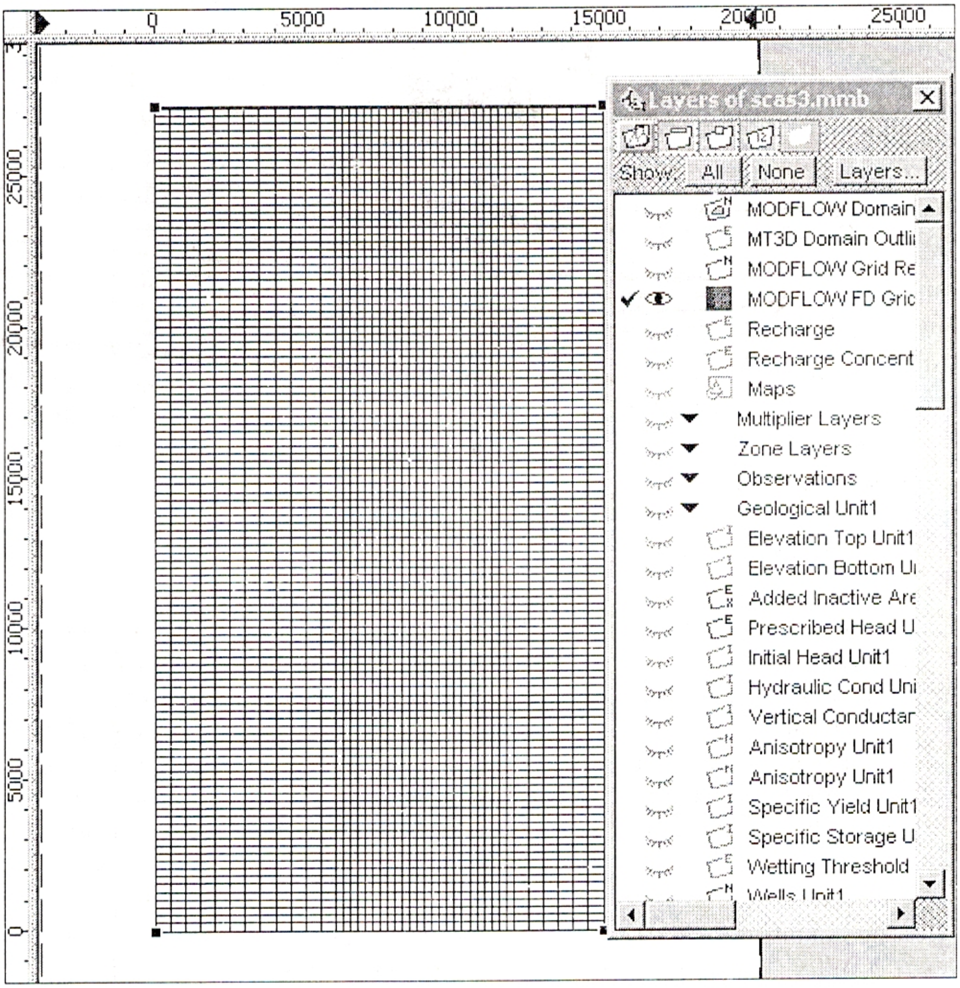


Fig. 2 Discretization with different layers.

Model calibration was done by taking the values of the period 1990-2002. For model calibration, conductivity and dispersivity were varied within reasonable limit. Figure 3 shows the comparison of observed and simulated head at an observation well whereas Fig. 4 shows the comparison of observed and predicted concentration at an observation well. Model was validated for the year 2003 and predictions were made upto 2010.

MANAGEMENT STRATEGIES

In order to control seawater intrusion and manipulate the freshwater in a coastal aquifer system, good and appropriate management techniques should be considered. There are two types of management problems in case of coastal aquifers. One is when the aquifer is not contaminated and the second one is the management once

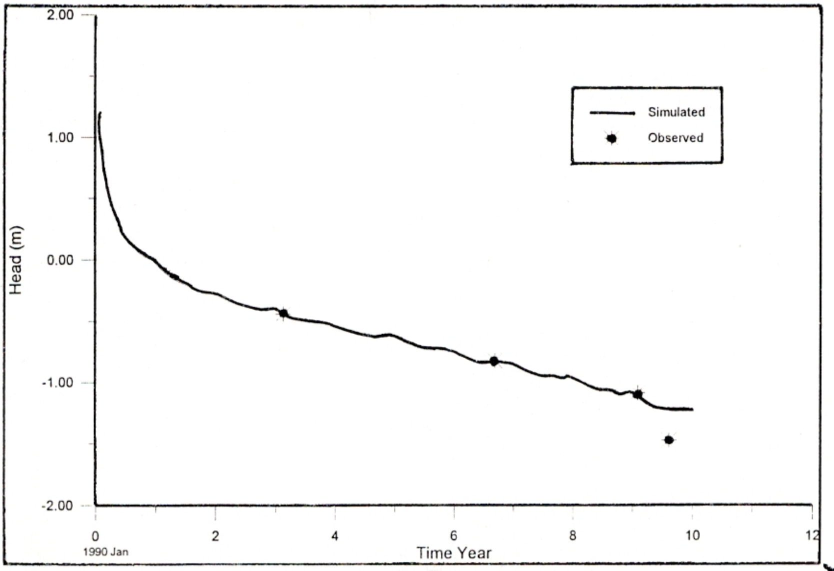


Fig. 3 Comparison of observed and computed head for an observation well.

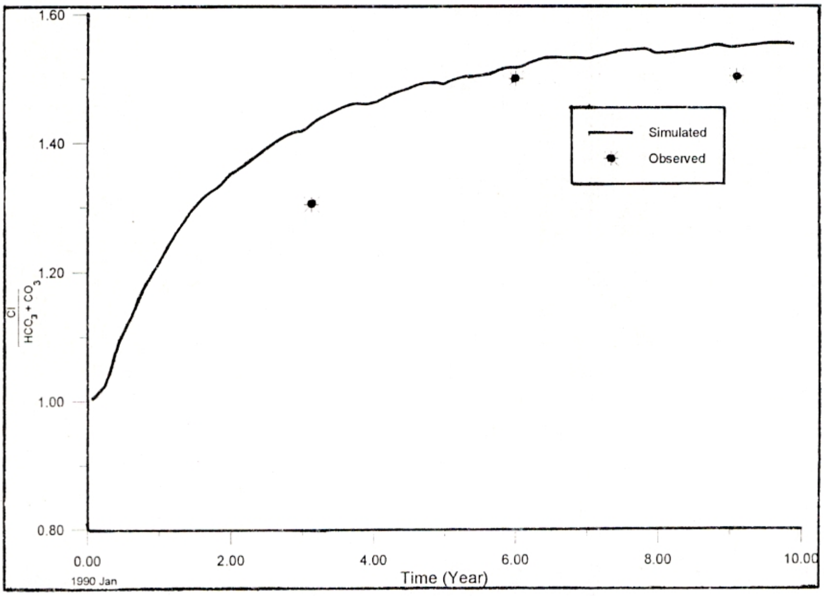


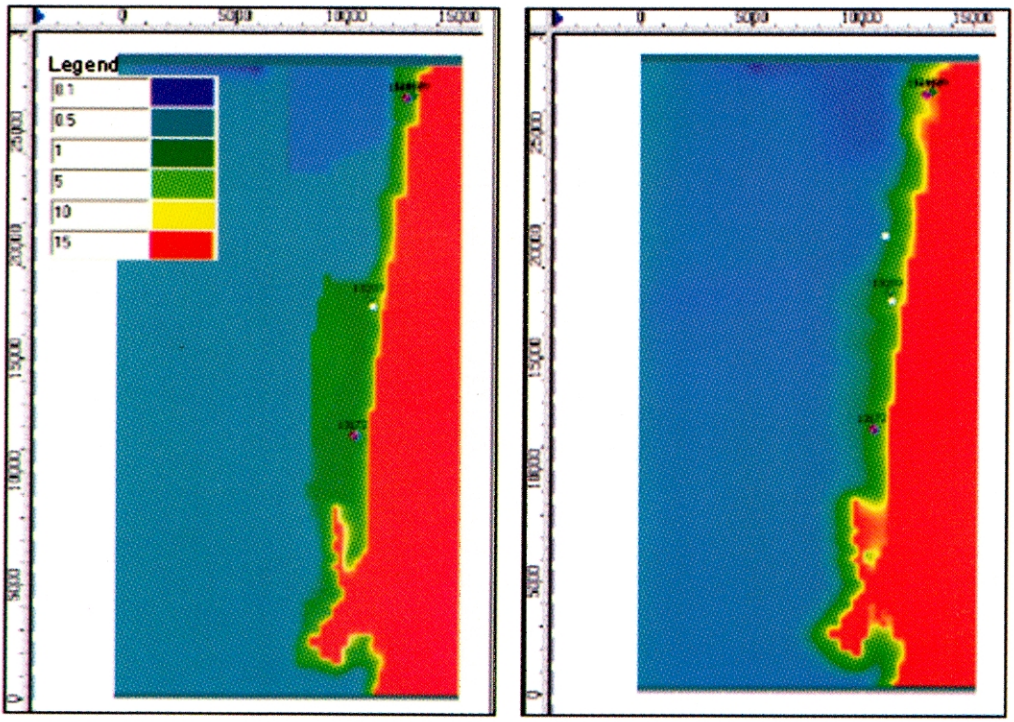
Fig. 4 Comparison of observed and computed $Cl/(HCO_3+CO_3)$ for an observation well.

the intrusion has taken place beyond the desirable extent. In the first case, there is always a freshwater flow towards the sea, so in this case the management decision is regarding how much can be the extent of intrusion. In the second case, management decision can be regarding the following:

1. Reduction of fresh water extraction (how much?)
2. Redistribution of pumping (optimization of pumping location)
3. Artificial recharge (how much to recharge?)
4. Extraction of seawater

Considering the above, the following scenarios were analysed for future predictions:

Scenario I Continuing the same demand and all other constraints as 2001 – The analysis showed that by the year 2010 there is a chance of advancement of interface upto 1 km. Figures 5(a) and 5(b) show the simulation results for this scenario.



(a) (b)

Fig. 5 Simulated $Cl/(HCO_3+CO_3)$ ratio (a) January 1990 (b) January 2010.

Scenario II Increase in demand by 1% each year – In this case, demand is increased and all other constraints are kept the same as in scenario I. Based on this analysis it was found that the advancement of seawater interface is upto 1.25 km by the year 2010. Compared to scenario I, the interface advances by an extra 250 m.

Scenario III Increase in demand by 1% each year and modernizing existing tanks – The results of this analysis show that there is one meter rise in water level due to modernizing of existing tanks located in the Injambakkam, Uttandi and Muttukadu areas. Currently, the Injambakkam, Uttandi and Muttukadu areas are not affected by seawater intrusion. But considering the future demand there may be a chance of intrusion. The analysis shows that modernizing the existing tanks would lead to one meter rise in water level. Thus, if the existing tanks are maintained properly, definitely there may not be a threat of seawater intrusion in this area

Scenario IV Increase in demand by 1% every year and constructing a barrier along the coast - In this scenario, a semi pervious barrier (with K = 0.0005 m/day) was provided in the area falling along Besant Nagar and Pallavakkam, at a distance of 500 m from the coast. Compared to scenario II, there is 500 m reduction in the length of interface, i.e. the toe of the interface is at 250 m from the barrier position.

Scenario V Pumping well optimization - In order to prevent further spreading of seawater into the aquifer, an optimization method was applied to obtain an optimal pumping strategy. For this purpose, the aquifer system was divided into 9 zones (Fig. 6). This zoning was carried out to facilitate the quantification of optimal pumping for control of saltwater intrusion in a given zone and for easier implementation. Only the first five zones were taken for the development of the optimization model because there is no threat of seawater intrusion in the last three zones. The computation of optimal pumping values for the five zones is discussed in the subsequent section.

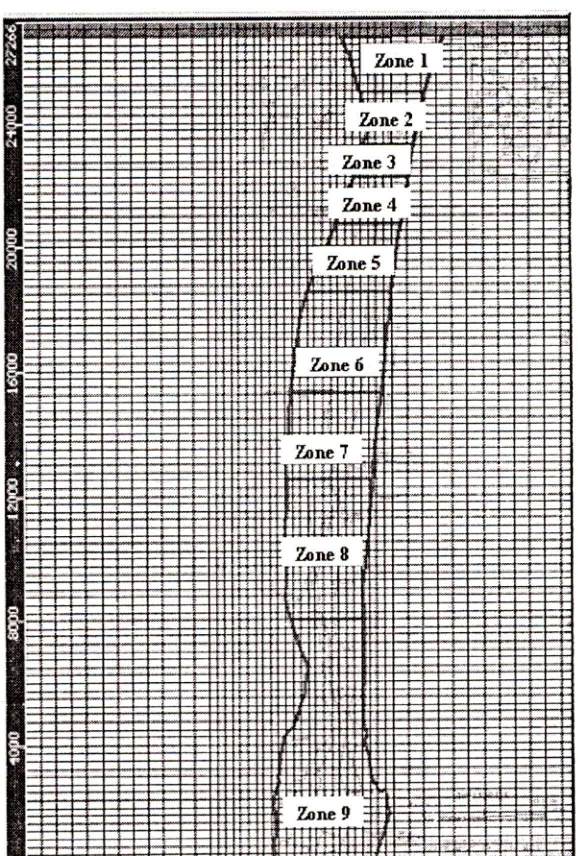


Fig. 6 Different zones in the study area.

OPTIMIZATION MODEL DEVELOPMENT

The problem is formulated as a multi objective optimization problem consisting of two objectives such as maximization of pumping and minimization of total cost of desalination considering the constraints on water levels and pumping. Multi objective interactions between the various trade-offs were analysed using multi objective evolutionary algorithm. The quantity of water being pumped from each zone during the year 2001-2002 was calculated based on the given rates and was given as the upper limit in the optimization; the lower limit was set to zero. The constraint on hydraulic head was assigned a safe value of 0.5 m. i.e. the hydraulic head in the aquifer should be 0.5 m above msl so that there is no danger of saltwater intrusion. The multi objective problem was formulated as follows:

$$\text{Maximize} \quad Z(Q) = \sum_{i=1}^{N} q_i \tag{3}$$

$$\text{Minimize} \quad Z(\text{demand} - Q) = \text{cost} \sum_{i=1}^{N} \left(\text{demand}_i - q_i\right) \tag{4}$$

$$h_j - h_j^* \geq 0.5, \quad j = 1,\ldots,m \tag{5}$$

$$0 < q_i < q_i^*, \quad i = 1,\ldots,n \tag{6}$$

where h_j is the computed hydraulic head at the observation point j; h_j^* is the minimum allowed hydraulic head (above msl) at the observation point j; q_i is the pumping rate from zone i; q_i^* is the maximum allowed pumping rate from zone i; m is the number of observation points (wells); and n is the number of zones.

For converting the head in terms of decision variables, the response matrix approach was used. In the response matrix approach an external groundwater simulation model is used to develop unit responses. Each unit response describes the influence of pulse stimulus upon output at points of interest throughout a system. As assemblage of the unit responses and a response matrix is included in the management model. Table 1 show the response at the control points due to unit stress for each decision variable. Equations (Eqs. (7)-(11)) that define the head in terms of decision variables are given below:

$$\text{H1} = h1 - \left(\left(0.04 \times x[1] + 0.01 \times x[2] + 0.01 \times x[3] + 0.01 \times x[4] + 0.01 \times x[5]\right)\right) \tag{7}$$
$$\text{H2} = h2 - \left(\left(0.005 \times x[1] + 0.022 \times x[2] + 0.019 \times x[3] + 0.028 \times x[4] + 0.028 \times x[5]\right)\right) \tag{8}$$
$$\text{H3} = h3 - \left(\left(0.001 \times x[1] + 0.002 \times x[2] + 0.051 \times x[3] + 0.011 \times x[4] + 0.001 \times x[5]\right)\right) \tag{9}$$
$$\text{H4} = h4 - \left(\left(0.001 \times x[2] + 0.01 \times x[3] + 0.042 \times x[4] + 0.004 \times x[5]\right)\right) \tag{10}$$
$$\text{H5} = h5 - \left(\left(0.001 \times x[2] + 0.004 \times x[4] + 0.049 \times x[5]\right)\right) \tag{11}$$

where H1, H2, H3, H4 and H5 are the heads at control location of zones 1-5; $h1$, $h2$, $h3$, $h4$, $h5$ are initial head values at control location of zones 1-5; and $x[1]$, $x[2]$, $x[3]$, $x[4]$ and $x[5]$ are the decision variables (pumping rate from each zone).

Table 1 Response at the control points.

Observation	Decision Variable	Response
*Z*1	*x*1	0.04
*Z*1	*x*2	0.01
*Z*1	*x*3	0.01
*Z*1	*x*4	0.01
*Z*1	*x*5	0.01
*Z*2	*x*1	0.005
*Z*2	*x*2	0.022
*Z*2	*x*3	0.019
*Z*2	*x*4	0.028
*Z*2	*x*5	0.028
*Z*3	*x*1	0.001
*Z*3	*x*2	0.002
*Z*3	*x*3	0.051
*Z*3	*x*4	0.011
*Z*3	*x*5	0.001
*Z*4	*x*1	0
*Z*4	*x*2	0.001
*Z*4	*x*3	0.01
*Z*4	*x*4	0.042
*Z*4	*x*5	0.004
*Z*5	*x*1	0
*Z*5	*x*2	0.001
*Z*5	*x*3	0
*Z*5	*x*4	0.004
*Z*5	*x*5	0.049

In the case of multi objective problems instead of finding a single optimum solution, an attempt is made to produce 'trade-offs' from which the decision maker will select one. The most popular approach to handle multiple objectives is to consider a set of the locally best alternatives, or the solutions that represent the optimal tradeoffs for the solution. These comprise the non-dominated frontier for the problem and the objective now becomes to find the set of solutions that are globally non-dominated (or Pareto Optimal). In other words, the objective is to find solutions to the problem such that there are no feasible solutions that would be better in one criterion without worsening at least one other criterion. This paper uses an elitist Non-dominant Sorting Genetic Algorithm (GA) - NSGA-II (Deb, 2001) to find a 'population' of non-dominated solutions. Table 2 shows the parameters of GA adopted for this study. Table 3 shows the feasible and non-dominated solution space and objective space obtained by the application of NSGA-II. Figure 7 shows the decision variable space for different generations.

Table 2 Parameters of GA.

Parameters	Value
Number of decision variables	5
Number of objective functions	2
Number of constraints	5
Number of bits assigned for each variable	10
Population size	50
Number of generations	100
Cross over probability	0.8
Mutation probability	0.02

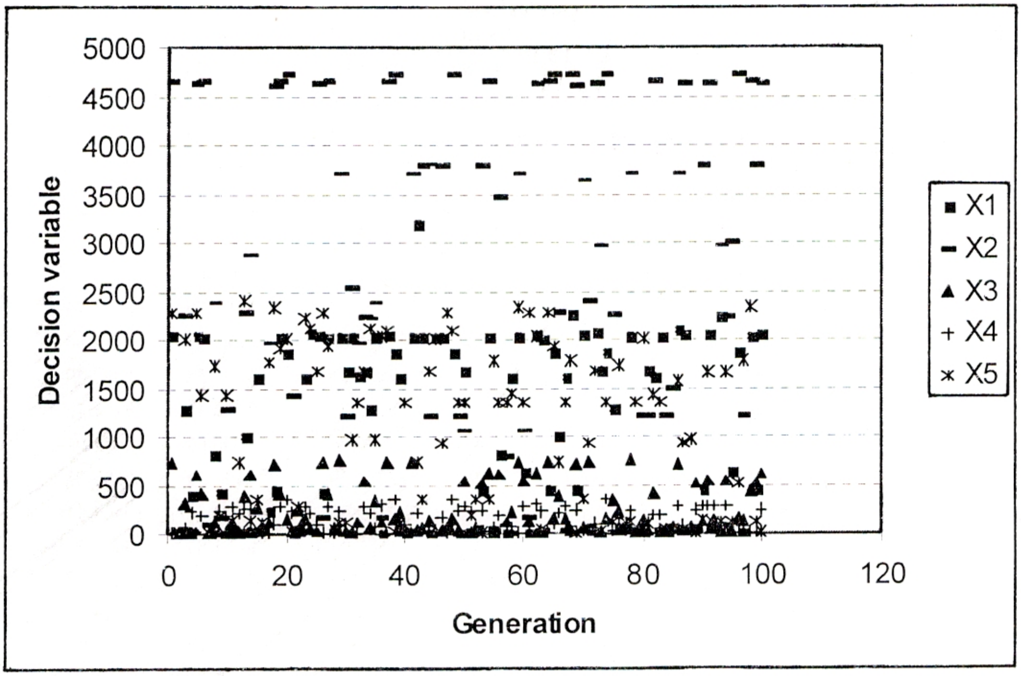


Fig. 7 Decision variable space for different generations.

From among the several solutions with different trade-offs provided by the model for the multi objective problem, the 12^{th} alternative given by the model is considered to be better. Table 4 shows the optimal pumping strategy from the various zones.

Figure 8 shows the trade-offs between total groundwater extraction and desalinated water (left over is met from the desalinated water). The graph shows a range of solutions, which represent the optimal trade-off for this problem rather than a single solution. Based on the decision makers choice of decision variables one can select the solution from the trade-off analysis. For instance, for the values of decision variables mentioned above, 927.5 m^3/d of groundwater and 13960.54 m^3/d of desalinated water can be used to satisfy the demand.

Table 3 Feasible and non-dominated solution space and objective space

$x1$	$x2$	$x3$	$x4$	$x5$	OBJ-1	OBJ-2
2059.68	4649.13	727.24	2.12	2267.46	9705.63	5182.41
0.00	9.23	0.78	3.53	2.57	16.11	14871.93
1267.01	2262.24	317.88	55.85	2000.70	5903.68	8984.36
399.45	9.23	6.20	223.39	20.52	658.80	14229.24
2059.68	4644.51	603.19	19.09	2267.46	9593.93	5294.11
2009.75	4662.98	404.71	183.10	1421.01	8681.55	6206.49
0.00	83.10	0.78	3.53	2.57	89.98	14798.06
817.63	2373.04	113.19	94.73	1733.94	5132.54	9755.50
418.18	156.97	21.71	243.19	179.55	1019.60	13868.44
6.24	1265.01	7.75	183.10	1421.01	2883.11	12004.93
56.17	9.23	113.19	264.75	133.38	576.73	14311.31
0.00	9.23	0.00	200.06	718.20	927.50	13960.54
1004.87	2271.47	378.35	253.79	2393.15	6301.64	8586.40
37.45	2871.66	601.64	253.44	133.38	3897.56	10990.48
1597.81	0.00	245.77	9.19	353.97	2206.74	12681.30
56.17	9.23	55.82	2.83	117.99	242.05	14645.99
230.93	1966.76	106.99	7.78	1759.59	4072.06	10815.98
461.87	4602.96	714.83	94.73	2323.89	8198.29	6689.75
2009.75	4662.98	404.71	275.71	1916.06	9269.20	5618.84
1859.95	4718.38	136.45	343.93	2005.83	9064.55	5823.49
6.24	1412.74	43.42	223.39	20.52	1706.32	13181.72
49.93	0.00	235.69	230.82	279.59	796.03	14092.01
1604.05	9.23	138.00	275.71	2221.29	4248.29	10639.75
2065.92	9.23	46.52	198.65	2103.30	4423.63	10464.41
2059.68	4644.51	22.48	91.90	1667.25	8485.83	6402.21
418.18	161.59	727.24	2.12	2267.46	3576.59	11311.45
2009.75	4662.98	404.71	275.71	1918.62	9271.77	5616.27
56.17	9.23	55.82	2.83	28.22	152.27	14735.77
2034.71	3716.53	739.64	223.39	102.60	6816.88	8071.16
1672.71	1191.14	26.36	2.83	117.99	3011.02	11877.02
2040.95	2520.78	7.75	16.26	959.31	5545.06	9342.98
1641.50	1966.76	106.99	7.78	1338.93	5061.96	9826.08
1672.71	2234.54	534.96	275.71	1659.56	6377.47	8510.57
1267.01	2225.30	46.52	199.00	2103.30	5841.14	9046.90
2034.71	2377.66	322.53	61.50	959.31	5755.71	9132.33
6.24	156.97	113.19	298.68	2036.61	2611.70	12276.34
2059.68	4649.13	727.24	2.12	2082.78	9520.95	5367.09
1859.95	4718.38	136.45	342.16	20.52	7077.47	7810.57
1597.81	0.00	218.64	47.37	84.65	1948.46	12939.58
6.24	9.23	33.34	94.73	1338.93	1482.48	13405.56
2034.71	3716.53	732.67	3.53	20.52	6507.97	8380.07

Contd…

Table 3 (Contd.)

*x*1	*x*2	*x*3	*x*4	*x*5	OBJ-1	OBJ-2
3201.86	9.23	37.21	200.06	718.20	4166.58	10721.46
2034.71	3776.55	47.29	9.19	353.97	6221.72	8666.32
6.24	1191.14	134.13	91.90	1667.25	3090.66	11797.38
2022.23	3799.64	22.48	9.90	1995.57	7849.82	7038.22
2034.71	3776.55	44.97	163.66	936.23	6956.12	7931.92

Table 4 Optimal pumping strategy for various zones.

Zone	Optimal Pumping m^3/d
1	0.0
2	9.23
3	0.0
4	200.06
5	718.20

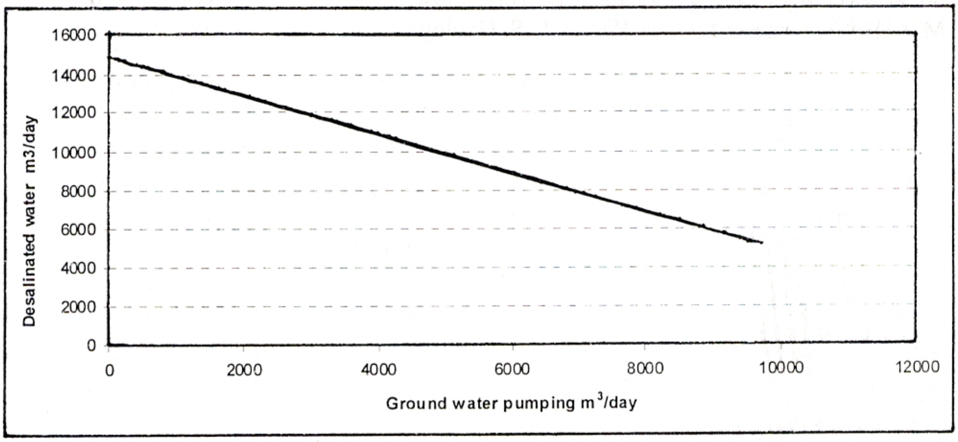


Fig. 8 The trade-off between total groundwater extraction and desalinated water.

CONCLUSIONS

It is concluded that there is an increasing trend of rapid movement of interface in the Besant Nagar and Thiruvanmiyur zones whereas in the Thiruvanmiyur-Kovalam zone, there is no definite clue for seawater intrusion. The water levels in this zone are just above mean sea level. The study also shows that modernizing the existing tank systems in the Injambakkam, Uttandi and Muttukadu zones has a great influence in reducing the movement of seawater interface movement considering the increase in water demand over the next ten years. It is found that construction of a semi pervious barrier also will help to reduce the seawater encroachment. Based on the model study it was found that the seawater freshwater movement is 20-30 m per year towards the landside. From the multi objective analysis a trade-off curve was developed between the total quantity of water extracted and the desalinated water. Rather than getting a single solution, the curve gives a range of solutions which represent the optimal trade-off for the problem considered.

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