Optimum Management of Basrah Coastal Aquifer Use under Seawater Intrusion

Ammar A. Akesh Al-Suraifi
Department of Civil Engineering
University of Basrah
College of Engineering

Ahmed M. Al-Kadhumi
Department of Civil Engineering
University of Basrah
College of Engineering

Abstract- **This study presents an attempt for establishment of sustainable development and management policies for utilization of Basrah coastal aquifer. The simulation/optimization approach is used with application to Um-Qasr aquifer in Basrah. In this research, 5 management schemes for sustainable use of a coastal aquifer exposed to seawater intrusion were developed and solved. The objective of the management models is to maximize the total amount of water pumped from the aquifer for beneficial use, and optimum location, numbers and redistribution of wells. Salt concentration of the pumped water from each of the pumping well was considered as a main constraint together with the minimum water head which is considered to control saltwater intrusion by heads balances with time. Solutions of the management schemes are based on a linkage between a simulation module SEAWAT and Simulated Annealing (SA) algorithm optimization module. The heads and concentrations, calculated by the simulation model based on pumping rates, are used in a SA optimization procedure to achieve an optimum solution. The five multi-objective management schemes were applied on Um-Qasr coastal aquifer. The results show that using simulation / optimization approach in Um-Qasr region can improve planning and management policies and can give better decision for aquifer utilization. The results show that the aquifer can safely increase its pumping rate by (175%) greater than its current abstraction according to the results of schemes 1.**

I. Introduction

Water resources should be managed in a sustainable way in order to respect the ecosystems and to preserve the resource availability. Water management includes a wide set of correlated problems that should be taken into account because they strictly interact with water demand, water availability, and water quality. Specifically, the water demand for the different uses (agriculture, industry, drinking water, public use) should be satisfied, water quality standards (that should be different for the various water uses) must be respected, the ecosystem should be preserved, sustainable policies and regulations should be developed, technological solutions must be tested, etc. [1]. Saline intrusion due to upconing toward pumping wells and the induced landward movement of seawater poses a particular challenge to sustainable water resource systems especially in coastal environments. Many coastal aquifers serve as major sources of freshwater supplies. These coastal areas are also very heavily urbanized, making the demand for freshwater more acute. Given the geographical repartition of needs, saline intrusion is now one of the main causes of groundwater quality degradation and one of the major constraints affecting groundwater management. The Um-Qasr aquifer on Arabian Gulf coast is chosen as the study area for good example in management applications (Fig. 1). Um-Qasr coastal aquifer met with the above problems and need for groundwater management due to many reasons, such as ports location, industrial, dense population, semi-arid and water scarcity, and its need for more future wells to supply Irrigation water for Basrah vegetation belt projects for that it is a good example for seawater intrusion problem due to over pumping and climate change impacts such as recharge decrease at last years. Fig. (2) depicts the simulation/optimization model for the optimal management of the Um-Qasr aquifer. In the simulation/optimization model, the modeler specifies the desired attributes of the hydrologic, quality and water resource management system (such as maximum salinity or allowed groundwater level declines) and the model determines from a set of several strategies a single management strategy that best meets the desired attributes.

II. The study area characteristics and simulations

Geographically, the Um-Qasr region is a part of the Iraqi coastal plain in the south east of Iraq in Basrah province, where it forms a main Iraq coast and ports Fig. (1). The Um-Qasr region is located on the north–western coast of the Arabian Gulf, between Easting–line (779030 - 785435) and Northing- line (3323445 - 3329553). Its area is about 39.2 km^2, with 6.5 km length, and between 6 and 7 km width. The Um- Qasr region is confined at Khur Al-Zubair from the east which is a part from Arabian Gulf, Safwan area from the north and west, and Kuwait country from the south. The population characteristics of the Um-Qasr city are strongly influenced by economical and industrial developments which have played a significant role in the growth and population distribution of the Um-Qasr. The present population of Basrah is estimated about 2.3 million [2] as illustrated in table (1) until 2025, the Um-Qasr's current total population is around 56000 people. The following table (1) shows the estimated district population of the Ministry of Planning and the total estimated population of the Mini M/P.

The land surface for Um-Qasr region have a relatively flat topography that rises about from 8 m above mean sea level (AMSL) for minimum point to about 14m (AMSL) for maximum surface point. The surface is semi flat without ridges and depressions as shown in Fig. (3).

The hydrogeology of Um-Qasr coastal aquifer consists of sandy soil and according to many soil investigation reports done at Um-Qasr city for its projects. The soil in Um-Qasr region is composed mainly of sands, gravel and silt. The sandy soil is found along the coastline extending from east to outside the western border of the region, at the form of sand dunes [3]. The Um-Qasr aquifer is unconfined with an average thickness of 28-33 m of sand and underlying with clay and sometimes clay and gravel layer [4]. The maximum saturated thickness of the aquifer ranges from 20 m near western aquifer boundary to 17 meters near the sea. Natural average groundwater heads decline smoothly east of Um-Qasr and gradually decline towards the sea as shown in Fig. (4).

The groundwater flow and salinity transport in Um-Qasr aquifer was simulated using the SEAWAT model [5]. SEAWAT uses a modified version of MODFLOW [6] to solve the variable density, ground water flow equation and MT3DMS [7] to solve the solute-transport equation. The numerical model covers an area of about 40 km^2. A finite difference grid was developed to adequately discretize the model domain [8]. The grid consists of 120 rows and 120 columns cross section, regularly spaced grid was constructed in horizontal and longitudinal directions and one cell (layer) in the vertical direction with variable thickness (ΔZ) according to the surface topographic and corresponds with land surface elevation as shown in Fig. (5).

More than 77 pumping wells are inventoried and represented in the model domain Fig. (6). For future model simulation the well withdrawal estimation was done according to the available data of population, population growth, number of wells, and groundwater abstraction within 2012-2014 which is estimated that the future annual withdrawal will increase at (2%). For simulation processes the basis for assigning hydraulic properties were the existing data from pumping test in the Um-Qasr aquifer, soil samples tests, previous soil investigations in the coastal plain and miscellaneous literature related to transport parameters. A summary of the aquifer hydraulic and transport properties that best describe the aquifer behavior in steady-state and transient simulation models, after model calibration, is presented in table (2). The final simulation result shows that seawater intrusion is happened in port wells at eastern parts of Um-Qasr area. It is predicted that between years 2015 and 2034, will induce a considerable quantity of seawater intrusion especially in the eastern part. Model results indicate that the extent of the isoline (TDS concentration = 10.0 kg/m^3) at aquifer will move about an additional 1.5 km in the eastern part. From the simulation results we can indicate the seawater intrusion (S.W.I.) rate of Um-Qasr aquifer for this conditions to be about 250 m/year. Fig.s 7 show the three dimensional model output results simulations for the extent of S.W.I. in the Um-Qasr aquifer at year 2034 without management approach.

III. Management model for um-qasr aquifer

The simulation annealing model, which is a heuristic optimization method, particularly those based on biological evolution principles, have been selected for Um-Qasr aquifer management, dealing with these problems; where this model will discussed in the next section.

3.1. Simulation Annealing Technique

Simulated annealing (SA) is a random-search technique which exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system [9]; it forms the basis of an optimization technique for combinatorial and other problems. Physical annealing is a process of attaining low energy states of a solid by initially melting the substance, and then lowering the temperature slowly, in such a way that the temperature remains close to the freezing point for a long period of time. At the end of the annealing process, the solid reaches its crystal state. In optimization, the objective function represents the energy in the thermodynamic process, while the optimal solution corresponds to the crystal state,[10]. Simulated annealing was developed in 1983 to deal with highly nonlinear problems [11]. SA approaches the global maximization problem similarly to using a bouncing ball that can bounce over mountains from valley to valley. In this algorithm, each decision variable can only take a discrete value from a specified set of possible values. Each combination of decision variables is called a conFig.uration.

IV. Methodology

One of the important parts of this methodology is the linkage between the optimization model and the 3D variable density seawater intrusion model for solving management-models with a nonlinearly non-convex constrained optimization problem. Basically, an iterative procedure is followed in which SA tests new policies of decision variables (pumping rates) for feasibility and optimality. The objective function and the constraints are functions of the state variables (heads and concentrations). These values are obtained from SEAWAT-3D simulation model. The model simulates the water movement in the porous medium, taking into account different forcing inputs such as pumping rates at wells (the decision variables) and computes migration of the salinity plume due to advection and dispersion processes; and computes the state variables. The heads and concentration are then used in a simulated annealing optimization procedure to achieve an optimum solution. Fig. (8) illustrates the linkage of the various components of the optimization solution procedure.

V. Formulation and application of the management schemes

To investigate whether an increase in current extraction rates are sustainable, a simulation/optimization models was it developed by the author and applied to the Um-Qasr aquifer. The study of management schemes application for the study area was conducted in two stages for each scheme; the formulation of the management schemes at the first stage, while the application of these formulated schemes with its results will be implemented at the second stage. Five management schemes were developed in this work. These developed schemes are based on managing the quantity and quality aspects of groundwater for sustainable use of the coastal aquifers in terms of groundwater pumping requiring a specified quality. Existing pumping locations (in plain view) are identified with number 1, through 57 in addition to 20 port wells , as shown in Fig. (6). This study was conceived on the basis of a desire to establish a management policy for the sustainable development and management of Um-Qasr aquifer system. To that end it was envisaged to achieve the following objectives:

• Evolution of a development strategy which will protect this part of Basrah aquifer in terms of quantity and quality for continued use by future generations,

• To determine the safe and sustainable yields and the limits of utilization for this aquifer system by establishing best values between alternatives from which decision makers may select optimum development strategy.

To achieve these objectives the multi-objective management schemes that was developed will be applied to Um-Qasr aquifer. For all schemes, the discharge of each pumping well should stay within the specified limits; the well pumping capacity (Q_{max} = 720 m^3/day) for the upper limit and no pumping (Q_{min} = zero) for the lower limit. This constraint is automatically satisfied by optimization processes in SA.

The total pumping constraint limited by either the aquifer yield, or the water demand depending on total city population and consumptions, were the total max. limit for aquifer yield constraint was estimated as follow:

Q_{max} = specific yield (S_y) x total aquifer volume (VT)
$\approx 74.1\text{x}10^6$ m^3/day.

The maximum demand constraint for year (2014) was estimated according to city population estimations that was done for the study area, the ports requirements and the study area characteristics where these value are estimated as:

D_{max} = 33600 *(m^3/day)* for year 2014.

In order to specify the limits of the management schemes constraints of salinity, the upper limits have to be determined before using the optimization process. The upper limit of the maximum salinity level (C_L) is a level of salinity that affect the uses of water for Irrigation, for R.O. units inflow which was proposed as (10000 mg/l). The results of simulation only without management for Um-Qasr aquifer using the above mentioned conditions using the SEWAT model, are shown in Fig.s (7).

The final management schemes results represents a lists of the specific optimum values for each pumping well and the total wells extractions, and we was referred to the total optimum pumping values only for each scheme application results due to high numbers values in case of showing all wells pumping for each scheme solution.

5.1. Formulation and Application of Management Scheme 1: Max. Yearly Pumping for Limiting Salinity for All Wells for 20 Future Years:

The goal of this management scheme is to get maximum water that can be extracted from the 77 existing wells of Um-Qasr aquifer while specify the maximum TDS concentrations levels for extracted water during all the 20^{th} future management years periods t.

Objective Function:

$$Max\ F = \sum_{t=2015}^{t=2034} \sum_{j=1}^{j=77} Q_{jt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

Where: Q_{jt} = is the pumping rate at jth well (m^3/yr) during the management period t (year).

Constraints:

In this problem, there are 77 observation cells (at wells locations) at which the aquifer drawdown and chloride concentrations must be calculated and constrained as follow:

1-	TDS concentration constraint:	$c_j \le C_L$	(2)
2-	Aquifer yield constraint:	$\sum_{j=1}^{j=77} Q_j \le Q_{max}$	(3)
3-	Water demand constraint:	$\sum_{j=1}^{j=77} Q_j \le D_{max}$	(4)
4-	Well capacity constraint:	$Q_{min} \le Q_j \le CAP.Q_j$	(5)
5-	Aquifer dewatering constraint:	$h_j \ge B_j + 1.0$	(6)
6-	Non-negativity constraints:	$Q_{min}, Q_{max}, Q_j, C_j, C_L \ge 0$	(7)

Where:

Q_j = is the pumping rate at jth well during the management period t (m^3/t).

h_j = is the head at well j (m).

c_j = the salinity (TDS) of the pumped water from jth well (mg/l).

C_L = specified salinity level (mg/l).

D_{max} = maximum water demand required for at study area during the management period t (m^3/day).

$CAP.Q_j$ = maximum pumping capacity of well j (m^3/day).

Q_{max} = upper limit of total pumping through the aquifer = S_y X VT (the aquifer safe yield (S_y) multiplying by the total aquifer wet volume) (m^3/day).

Q_{min} = zero for the lower limit pumping (m^3/day).

B_j = bottom elevation of the aquifer at cell of well j below mean sea level (m). The purpose of this constraint is to ensure that hydraulic heads do not decrease below a level of 1m above the bottom elevation of the aquifer at each dewatering cell.

According to scheme 1, the mathematical expression for constraints as follows:

1-	*TDS concentration constraint:*	$c_j \le 10000$ *(mg/l)*
2-	*Aquifer yield constraint:*	$\sum_{j=1}^{j=77} Q_j \le 74.1$*(MCM/day)*
3-	*Water demand constraint:*	$\sum_{j=1}^{j=77} Q_j \le$ *Max. Demand at this year (m^3/day)*
4-	*Well capacity constraint:*	$0.0 \le Q_j \le 720$ *(m^3/day)*
5-	*Dewatering constraint:*	$h_j \ge -19$ *(m)*

Where the maximum demand constraint for each year during (2015-2034) are varied according to population estimations that are done for the study area, and these values are as shown in table 3.

The results of solution of scheme 1 with its constraints are presented in tables 4 and 5 also Fig. 9 shows the water tables heads and the contour of 10000(mg/l) TDS salinity distribution at the aquifer resulting from optimal water withdrawal of scheme 1 at the end of year 2034.

5.2. Formulation and Application of Management Scheme 2: Max. Yearly Pumping for Limiting Heads for All Wells for 20 Future Years:

The goal of this management scheme is to maximize groundwater withdrawal from 77 existing wells while prevent seawater intrusion through the pumping well by controlling the hydraulic heads at all well cells to be above specified value (h_c) which is above or equal to mean sea level for all management periods t (years) during all the 20th future management years.

Objective Function:

$$Max\ F = \sum_{t=2015}^{t=2034} \sum_{j=1}^{j=77} Q_{jt}$$

Constraints:

In addition to this, another constraint on the hydraulic head at each pumping well j is added in order to prevent seawater intrusion by controlling the possible changes of groundwater flow direction due to undesired drop in groundwater head.

Where: The pumping from the aquifer is subject to the same constraints of scheme 1 as mentioned in equations (3-7). And;

The head constraint: $h_j \geq h_c$ …………………………….(8)

Where:

h_c = specified altitude value above mean sea level (0 m) during all management periods.

According to the scheme 2 management objective function with its relevant constraints, the mathematical expression for constraint as follows:

1-	*The head constraint:*	$h_j \geq 0.0$ (m)
2-	*Aquifer yield constraint:*	$\sum_{j=1}^{j=77} Q_j \leq 74.1$(MCM/day)
3-	*Water demand constraint:*	$\sum_{j=1}^{j=77} Q_j \leq 33600$ (m^3/day)
4-	*Well capacity constraint:*	$0.0 \leq Q_j \leq 720$ (m^3/day)
5-	*Dewatering constraint:*	$h_j \geq -19$ (m)

The results of solution of scheme 2 for the 20 years periods with the constraint of minimum head (h_{min}) of 0.0(m) above mean sea level (AMSL) are presented in tables 4 and 5. The water tables heads and aquifer 10000 mg/l TDS salinity distribution resulting from water withdrawal with optimal solutions of this scheme at the end of year 2034 are shown in Fig. 10.

5.3. Formulation and Application of Management Scheme 3: Max. Yearly Pumping From All Wells for Controlling Continues Flow Direction Towards the Sea for 20 Future Years:

The goal of management scheme 3 is to maximize groundwater withdrawal from 77 existing wells while preventing seawater intrusion towards the pumping wells by controlling the groundwater flow direction to be towards the sea side only. These constraints will be achieved by controlling the hydraulic heads at two groups of controlling wells near the coast and coastal cells for all management years during all the 20th future management years.

Objective Function:

$$Max\ F = \sum_{t=2015}^{t=2034} \sum_{j=1}^{j=77} Q_{jt}$$

Constraints:

The pumping from the aquifer at this management scheme is subject to the same constraints of scheme 2 as mentioned in equations (3-8) but the formulation of equation (8) must deal with control coastal cells only so that these equations will modify to:

The head constraint: $h_i \geq 0$ and $h_k \geq h_c$

Where (k=1,2,…..57) for city wells , (i=1,2,…..113) and h_i the hydraulic head at saltwater control cell i as defined previously.

The city wells cells constrained to be at or greater than a specified values h_c above mean sea level (0.1 m). According to this management scheme, the Constraints as follow:

1-	*The head constraint:*	$h_i \geq 0.0$, $h_k \geq 0.1$ (m) (i=1,2,..113) ,(k=1,2,..57)
2-	*Aquifer yield constraint:*	$\sum_{j=1}^{j=77} Q_j \leq 74.1$(MCM/day)
3-	*Water demand constraint:*	$\sum_{j=1}^{j=77} Q_j \leq$ Max. Demand at this year (m^3/day)
4-	*Well capacity constraint:*	$0.0 \leq Q_j \leq 720$ (m^3/day)
5-	*Dewatering constraint:*	$h_j \geq -19$ (m)

Solutions of this management scheme for the 20 year periods at specified minimum heads are summarized in tables 4 and 5. The water tables heads and aquifer specified contour salinity distribution resulting from scheme 3 at year 2034 are shown in Fig. 11.

5.4. Formulation and Application of Management Scheme 4: Optimum Redistribution of All wells for Limiting Salinity and Max. Pumping from Modified Wells for 20 Future Years:

This management scheme consist of two phases; its concern with deactivating or (shutting down) some wells at the aquifer for the first phase, and then to maximize groundwater withdrawal from the remaining optimal active existing wells. TDS concentrations levels for extracted water from these wells (active wells) are to be controlled during the management periods.

Objective Function:

$$Max\ F = \sum_{t=2015}^{t=2034} \sum_{j=1}^{j=R} Q_{jt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Constraints:

The pumping from the aquifer at this management scheme is subject to the same constraints of schemes 1 as mentioned in equations (2-7) but the formulation of all equations must deal with the total active wells cells

Where j=R and;

(R) is the total number of remaining active wells after first phase solution.

The results of first phase solution of this scheme (optimal wells numbers and locations) show that the optimal amount of wells are 52 wells instead of the old amount of 77 wells (by shutdown of 25 wells from the aquifer). The locations of the remaining 52 selected wells are shown in Fig. 12.

The second phase was the optimal solution for this management scheme with the constraints depending on first phase result for the 52 wells layout and it can be expressed as follows:

1-	*TDS concentration constraint:*	$c_j \leq 10000$ (mg/l)
2-	*Aquifer yield*	$\sum_{j=1}^{j=77} Q_j \leq 74.1$(MCM/day)

constraint:

3- *Water demand constraint:* $\sum_{j=1}^{j=52} Q_j \leq$ *Max. Demand at this year (m^3/day)*

4- *Well capacity constraint:* $0.0 \leq Q_j \leq 720$ *(m^3/day)*

5- *Dewatering constraint:* $h_j \geq -19$ *(m)*

The results of solution of this scheme are presented in tables 4 and 5. Fig. 12 shows the water tables heads and the contour of 10000(mg/l) TDS salinity distribution at the aquifer resulting from optimal water withdrawal of this scheme at the end of year 2034.

5.5. Formulation and Application of Management Scheme 5: Max. Yearly Pumping at Aquifer Safe Yield with Recharges for 20 Future Years:

The goal of management scheme 5 is to control groundwater withdrawal from 77 existing wells to be not more than aquifer safe yield.

Safe yield is defined as groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawal and the annual amount of natural recharges in the active management areas. In this management scheme, it was assumed that recharge sources were from rainfall and lateral flow which is estimated from available information regarding subsurface lateral inflow to Um-Qasr area. As such the total recharge is calculated as:

i) Rainfall Recharge:

Total average rainfall depth (on the study area) till year 2012 = 0.151 m/year

Total rainfall volume (m^3/year) = Total rainfall m/year × Affective Surface area

= 2544650 m^3/year.

Percentage of percolation water from rainfall is about 20%, then:

Rainfall recharge volume

= 0.20 × 2544650 = 508930 m^3/year.

ii) Lateral flow Recharge:

From SEAWAT result; average lateral velocity from the western border (source flow direction) at the steady state simulation and case of no pumping from all wells on the study area at year 2013 ≈ 0.4 m/day ≈ (146 m/year).

From conceptual model dimensions; the effective cross-sectional flow area at flow western boundary = 29013 m^2.

then: Total lateral recharge volume (m^3/year) = Average annual recharge velocity (m/year) × Affective cross-sectional area

= 146 × 29013 = 4235898 m^3/year.

The total recharges at study area

= 4235898 + 508930 = 4,744,828 m^3/year.

{where average lateral velocity of 0.4 m/day was estimated from SEAWAT results for flow velocity values and effective cross-sectional area of 29013 m^2 was estimated from aquifer depth and boundary lengths after formulate of conceptual model.

The goal of this management scheme is the total yearly discharge from all wells at study area should not exceed the total recharge amount calculated above or a max. of (13000 m^3/day) and also to avoid aquifer dewatering, and satisfy water demand and wells capacity limitations throw 20 future years.

Objective Function:

$$\boldsymbol{Max\ F} = \sum_{t=2015}^{t=2034} \sum_{j=1}^{j=77} \boldsymbol{Q_{jt}}$$

Where Q_{jt} in (m^3/year)

Constraints:

Where: The pumping from the aquifer at this management scheme is subject to the same constraints of scheme 1 but the formulation of equation (2) must deal with the new aquifer safe yield of (13000 m^3/day) and these Constraints expressed as follow:

1- *Total extraction (safe yield) constraint:* $\sum_{j=1}^{j=77} Q_j \leq 13000$ *(m^3/day)*

3- *Water demand constraint:* $\sum_{j=1}^{j=77} Q_j \leq D_{max}$. *($m^3$/day)*

4- *Well capacity constraint:* $0.0 \leq Q_j \leq 720$ *(m^3/day)*

5- *Dewatering constraint:* $h_j \geq -19$ *(m)*

Solutions of this management scheme for the 20 future year periods at specified maximum total extraction values are summarized in tables 4 and 5.

VI. Summary and conclusions for management schemes applications

This research presented the numerical solution of maximum pumping rate of wells located in Um-Qasr coastal aquifer which might be effected by seawater intrusion. Five multi-objective management schemes with different objective functions for sustainable exploitation from coastal aquifer were formulated and solved. Optimal pumping rates for Um-Qasr aquifer were obtained under different management schemes applications. Tables 4, and 5 summarizes optimal total pumping rates and annual optimal rates for each scheme. The groundwater heads and seawater intrusion at optimal pumping rate from Um-Qasr wells is shown in Fig.s (9 – 12) and a Comparison among current and future years abstractions with optimal abstractions are shown in Fig.s (13 and 14).

The five management schemes control the extraction for 20 future years and for each pumping year.

From the results of application the five management schemes at Um-Qasr aquifer we can conclude that:

- For current year management the salinity constraints schemes (1 and 4) gave highest abstraction values than the heads constraint schemes (2 and 3) which gave the lowest values.
- The outcome from the management models shows that $4.75x10^6 m^3$/yr can be safely pumped out from the Um-Qasr aquifer to ensure aquifer safe yield with recharges at the future was the best abstractions among all schemes.
- Optimal value for Um-Qasr wells numbers was 52 wells instead of the old amount of 77 wells according to result of scheme 4.

To discuss and compare the results of schemes as summarized in tables 4, and 5 and Fig.s 13 and 14, the following remarks can be noted:

VII. References

[1] Marco Antonellini, Giovanni Gabbianelli, Riccardo Minciardi, Michela Robba, Roberto Sacile, Elisa Ulazzi, "AN OPTIMAL DECISION MODEL FOR COASTAL AQUIFERS MANAGEMENT", 2005 IFAC.

[2] Tokyo Engineering Consultants Co., Ltd. and NIPPON KOEI CO., LTD, The Feasibility Study on Improvement of the Water Supply System In Al-Basrah City and Its Surroundings in The Republic of Iraq, INTERIM REPORT, JAPAN INTERNATIONAL COOPERATION AGENCY (JICA), 2006.

[3] Soil Investigation Reports for different regions and projects at Um Qasr city, Basra, IRAQ.

[4] BUCCA Water Production Treatment Plant and Storage, Design Analysis Report, by Areebel Co.. CAMP BUCCA-UM QASR, IRAQ, 2008.

[5] Visual MODFLOW Premium, Demo Tutorial, Waterloo Hydrogeologic Inc.

[6] J.M. McDonald and A.W. Harbaugh, "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model", in Techniques of Water Resources Investigations, U.S.G.S., Book 6. Reston, VA: U.S. Geological Survey, 1988.

[7] Anna Buseman-Williams, David Farrell and Alexander Sun, SOFTWARE VALIDATION TEST PLAN AND TEST REPORT FOR MODULAR THREE-DIMENSIONAL MULTISPECIES TRANSPORT MODEL (MT3DMS) VERSION 4.5, Center for Nuclear Waste Regulatory Analyses, 2005. 91-2. Zheng, C.M. and P.P. Wang. "MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide." Contract Report SERDP-99-1. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center. 1999.

[8] Thomas E. Reilly and Arlen W. Harbaugh, " **Guidelines for Evaluating Ground-Water Flow Models",** Scientific Investigations Report 2004-5038. U.S. Department of the Interior, U.S. Geological Survey.

[9] Franco Busetti, " Simulated annealing overview".

[10] Visual MODFLOW User's Manual, 2010.1, Dynamic Groundwater Flow and Contaminant Transport Modeling Software, , Schlumberger Water Services, Waterloo, Ontario, CANADA, N2L 5J2.

[11] S. Kirkpatrick; C. D. Gelatt; M. P. Vecchi, " Optimization by Simulated Annealing", Science, New Series, Vol. 220, No. 4598. (1983), pp. 671-680.

Scheme-1, (yearly management):		
Total Optimal Extraction	**Comparison**	**Governing Constraints**
current year optimal total extraction was ($10.61x10^6 m^3/yr$).	increasing rate of about 170% from current non managed extraction.	limiting constraint is the TDS concentration (eq. 2).
future year of 2034 total optimum extraction was ($2.93x10^6 m^3/yr$).	at a decreasing rate of about 33% from non-managed year extraction.	limiting constraint is the TDS concentration (eq. 2).
This mean that the aquifer can yield much water at current year only without seawater intrusion reaching to the pumping wells, while its can extract $2.93x10^6 m^3/yr$ to ensure no seawater intrusion to pumping wells as shown in Fig. (9).		

Scheme-2, (yearly management):		
Total Optimal Extraction	**Comparison**	**Governing Constraints**
current year optimal total extraction was ($2.21x10^6 m^3/yr$).	at a decreasing rate of about 40% from current non managed extraction.	limiting constraint is the heads constraint (eq. 8).
future year of 2034 total optimum extraction was ($2.48x10^6 m^3/yr$).	at a decreasing rate of about 28% from non-managed year estimated extraction.	limiting constraint is the heads constraint (eq. 8).
This mean that the aquifer can safely yield these values of water at current and future years to ensure no seawater intrusion reaching to the pumping wells, where none of any heads elevations contours decrease than 0.0 m at all the future years for all wells as shown in Fig. (10).		

Scheme-3, (yearly management):		
Total Optimal Extraction	**Comparison**	**Governing Constraints**
current year optimal total extraction was ($2.04x10^6 m^3/yr$).	at a decreasing rate of about 30% from current non managed extraction.	limiting constraint is the heads constraint (eq. 8).
future year of 2034 total optimum extraction was ($3.23x10^6 m^3/yr$).	at a decreasing rate of about 37% from non-managed year estimated extraction.	limiting constraint is the heads constraint (eq. 8).
This means that aquifer can extract these values of water at current and future years to ensure the groundwater flow direction to be towards the sea and so no seawater intrusion reaching to the pumping wells at all the future years as shown in Fig. (11) where the contour of heads elevations show the flow directions towards the sea.		

Scheme-4, (yearly management):		
Total Optimal Extraction	**Comparison**	**Governing Constraints**
current year optimal total extraction was ($3.38x10^6 m^3/yr$).	at a decreasing rate of about 80% from current non managed extraction.	limiting constraint is the TDS concentration constraint (eq. 2).
future year of 2034 total optimum extraction was ($3.39x10^6 m^3/yr$).	at a decreasing rate of about 57% from non-managed year estimated extraction.	limiting constraint is the TDS concentration constraint (eq. 2).
First phase solution show that the optimal wells numbers was 52 wells, and indicate the optimal location of these wells by selection from old wells locations as shown in Fig. (12). Second phase solution show that that the aquifer can extract these quantities of water at current and future years without seawater intrusion reaching to the any of pumping wells as shown in Fig. (12).		

Scheme-5, (yearly management):		
Total Optimal Extraction	**Comparison**	**Governing Constraints**
current year optimal total extraction was ($4.74x10^6 m^3/yr$).	at a decreasing rate of about 60% from current non managed extraction.	Limiting constraint is the aquifer yield constrains (eq. 3).
future year of 2034 total optimum extraction was ($4.74x10^6 m^3/yr$).	at a decreasing rate of about 60% from non-managed year estimated extraction.	Limiting constraint is the aquifer yield constrains (eq. 3).
This mean that the aquifer can extract this value of water for all years to ensure the aquifer safe yield during its operation without any seawater intrusion or aquifer dewatering.		

Table I Estimated Population of Basrah and Um-Qasr by the Ministry of Planning

District	2003	2005	2006	2010	2015	2020	2025
Al-Basrah	1762000	1851201	1899854	2094464	2312458	2553140	2818873
Um-Qasr	43000	45177	46365	51114	56433	62307	68792

Table II Um-Qasr aquifer parameter after calibration

Parameter	Value
Hydraulic conductivity K_{xy}	78 m/d
Hydraulic conductivity K_z	50 m/d
Total porosity	0.33 %
Effective porosity	0.30 %
Specific yield	0.22
α_L : longitudinal dispersivity	10 m
α_T : transverse dispersivity	1.0 m
α_v : vertical dispersivity	0.1 m

Table III Estimated annual water demand ($D_{max.}$) for Um-Qasr region based on population estimations for 20 years.

Years	Estimated Max. Demand (m^3/day)	Years	Estimated Max. Demand (m^3/day)	Years	Estimated Max. Demand (m^3/day)	Years	Estimated Max. Demand (m^3/day)
2015	34300	2020	37700	2025	41400	2030	45600
2016	34900	2021	38400	2026	42200	2031	46500
2017	35600	2022	39100	2027	43000	2032	47400
2018	36300	2023	39800	2028	43800	2033	48300
2019	37000	2024	40600	2029	44700	2034	49200

Table IV Optimum-Max. yearly Water Extraction From All The Existing Wells During 20 Year Management Periods (2015-2034) (x10^6 m^3/year)

Years of Management Periods	Management Schemes				
	Scheme-3	Scheme-4	Scheme-5	Scheme- 6	Scheme-7
2015	10.614	2.213	2.046	3.38	4.745
2016	6.257	2.129	2.499	3.55	4.745
2017	4.752	2.267	2.631	3.63	4.745
2018	4.037	2.242	2.699	3.37	4.745
2019	3.639	2.206	2.777	3.39	4.745
2020	3.413	2.242	2.816	3.18	4.745
2021	3.250	2.273	2.858	3.26	4.745
2022	3.126	2.265	2.888	3.24	4.745
2023	3.012	2.290	2.911	3.09	4.745
2024	2.976	2.308	2.958	3.10	4.745
2025	2.927	2.337	2.990	3.17	4.745
2026	2.917	2.342	3.017	3.18	4.745
2027	2.909	2.376	3.057	3.27	4.745
2028	2.881	2.380	3.079	3.33	4.745
2029	2.874	2.400	3.103	3.30	4.745
2030	2.877	2.420	3.126	3.31	4.745
2031	2.884	2.424	3.161	3.38	4.745
2032	2.895	2.445	3.177	3.35	4.745
2033	2.910	2.469	3.214	3.45	4.745
2034	2.933	2.486	3.238	3.39	4.745

Table V Optimum-Max. Total Water Extraction From All The Existing Wells During 20 Year Management Periods (2015-2034) ($x10^6$ m^3/management period -day)

Total Management Periods for 20-years		**Management Schemes**				
		3	**4**	**6**	**8**	**9**
2014 2015	365 - Days	10.614	2.213	2.046	3.382	4.745
2015 - 2016	730 - Days	12.513	4.257	4.997	7.093	9.490
2015 - 2017	1095 - Days	14.257	6.802	7.893	10.886	14.235
2015 - 2018	1460 - Days	16.148	8.966	10.796	13.478	18.980
2015 - 2019	1825 - Days	18.194	11.028	13.886	16.954	23.725
2015 - 2020	2190 - Days	20.477	13.454	16.898	19.064	28.470
2015 - 2021	2555 - Days	22.753	15.914	20.006	22.827	33.215
2015 - 2022	2920 - Days	25.009	18.117	23.105	25.935	37.960
2015 - 2023	3285 - Days	27.106	20.608	26.201	27.836	42.705
2015 - 2024	3650 - Days	29.756	23.082	29.576	30.985	47.450
2015 - 2025	4015 - Days	32.202	25.706	32.886	34.827	52.195
2015 - 2026	4380 - Days	35.001	28.101	36.199	38.134	56.940
2015 - 2027	4745 - Days	37.821	30.894	39.743	42.497	61.685
2015 - 2028	5110 - Days	40.338	33.319	43.111	46.662	66.430
2015 - 2029	5475 - Days	43.116	36.005	46.552	49.568	71.175
2015 - 2030	5840 - Days	46.028	38.716	50.011	52.977	75.920
2015 - 2031	6205 - Days	49.026	41.204	53.743	57.455	80.665
2015 - 2032	6570 - Days	52.117	44.011	57.181	60.338	85.410
2015 - 2033	6935 - Days	55.284	46.913	61.062	65.473	90.155
2015 - 2034	7300 - Days	58.664	49.723	64.767	67.65	94.900

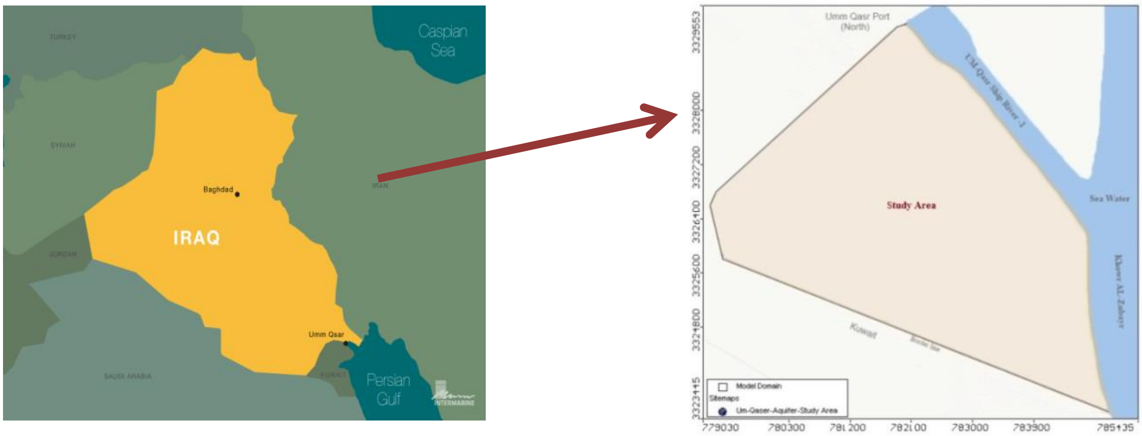

Fig. 1 Location map of the Um-Qasr region

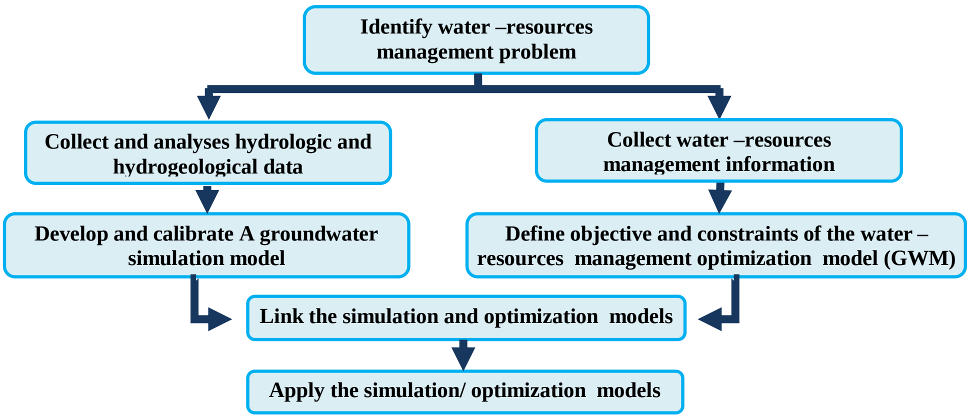

Fig. 2 The Steps for the Development and Application of a Groundwater Simulation/Optimization Model for the Um-Qasr Aquifer

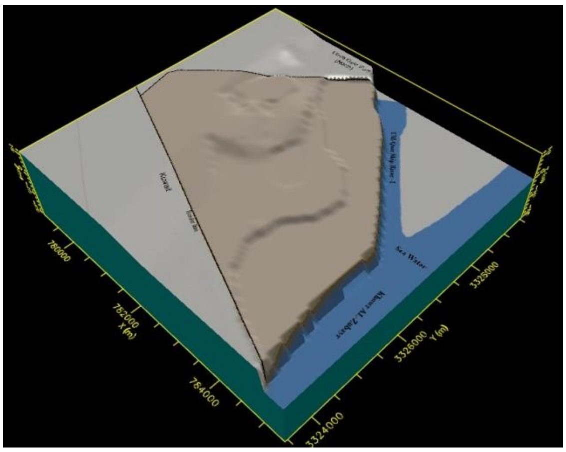

Fig. 3 Topographic of Um-Qasr aquifer.

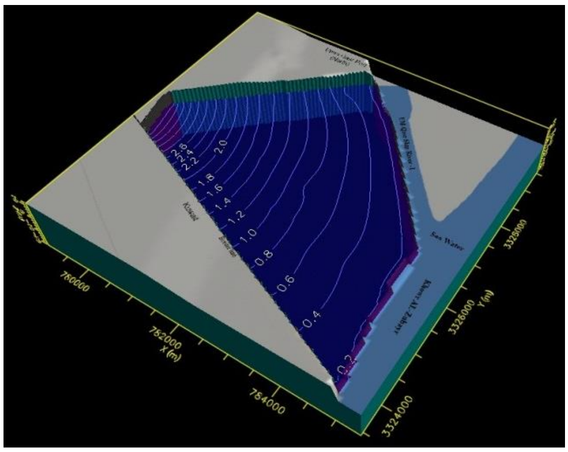

Fig. 4 Initial G.W. levels contours for Um-Qasr aquifer.

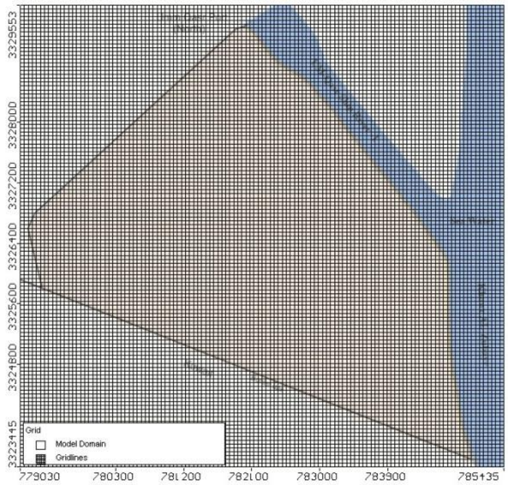

Fig. 5 Model grids and cells discretization.

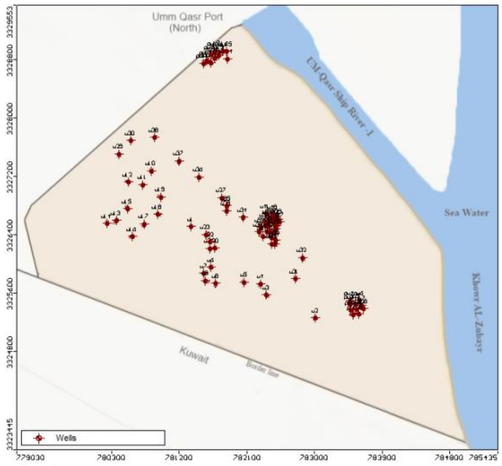

Fig. 6 Distribution of existing wells in the study area.

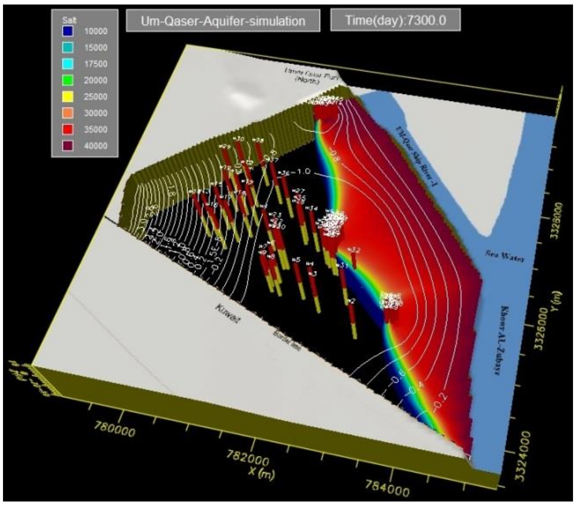

Fig. 7 3-D Simulated extent of seawater intrusion in Um-Qasr aquifer after (7300) days.

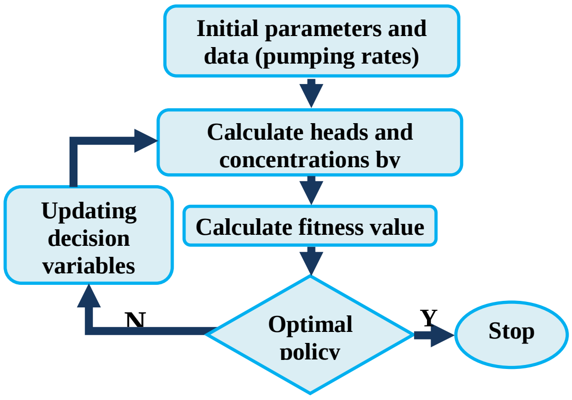

Fig. 8 The optimization-simulation solution procedure.

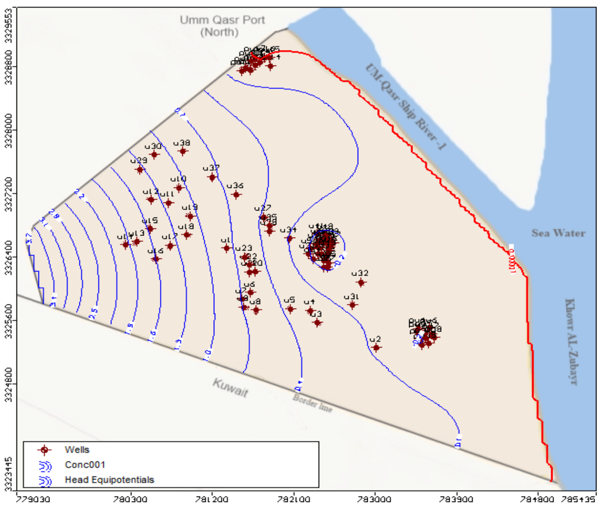

Fig. 9 The simulation of water heads and contours for the 10000 (mg/l) TDS concentration at the end of 7300 days at year 2034 based on the scheme -1 optimal pumping.

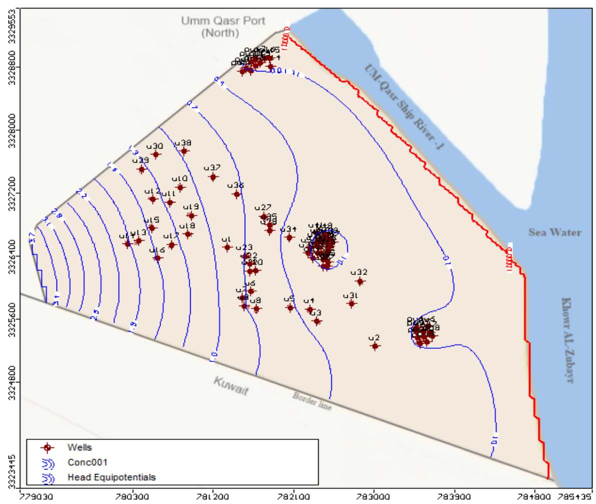

Fig. 10 The simulation of water heads and contour for the 10000 (mg/l) TDS concentration at the end of 7300 days at year 2034 based on the Scheme-2 optimal pumping.

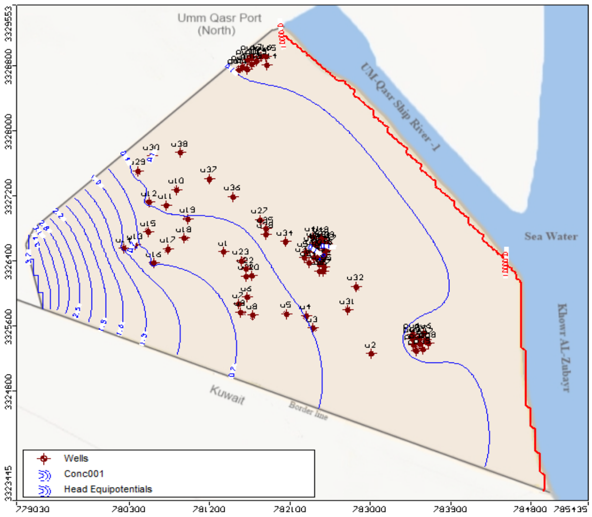

Fig. 11 The simulation of water heads and contour for the 10000 (mg/l) TDS concentration at the end of 7300 days at year 2034 based on the scheme -3 optimal pumping.

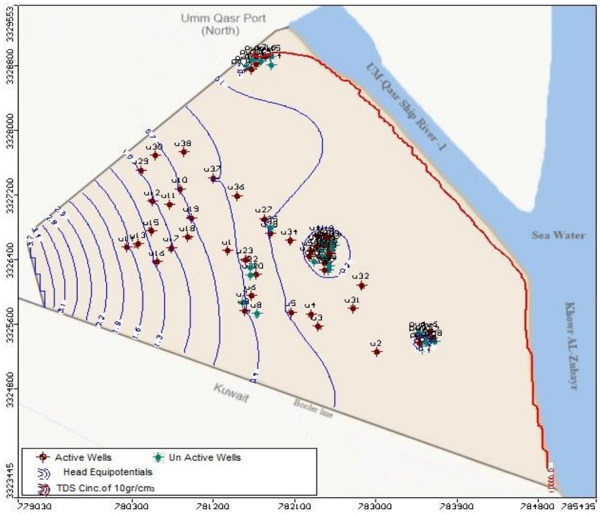

Fig. 12 The selected wells optimal location and simulation of water heads and contour for the 10000 (mg/l) TDS concentration at the end of year 2034 based on the Scheme-4.

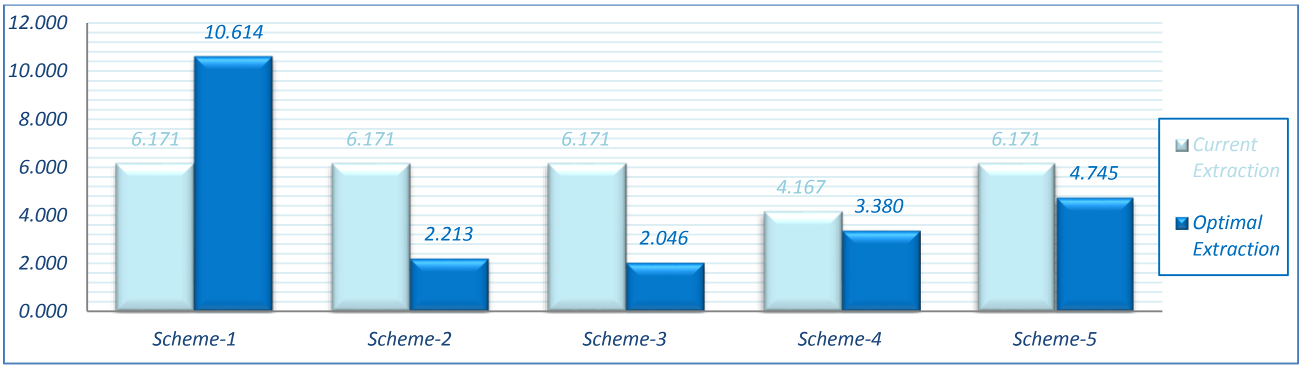

Fig. 13 Comparison among current year (2014) total extractions at optimum solutions of all schemes (the values x 10^6 m^3/yr).

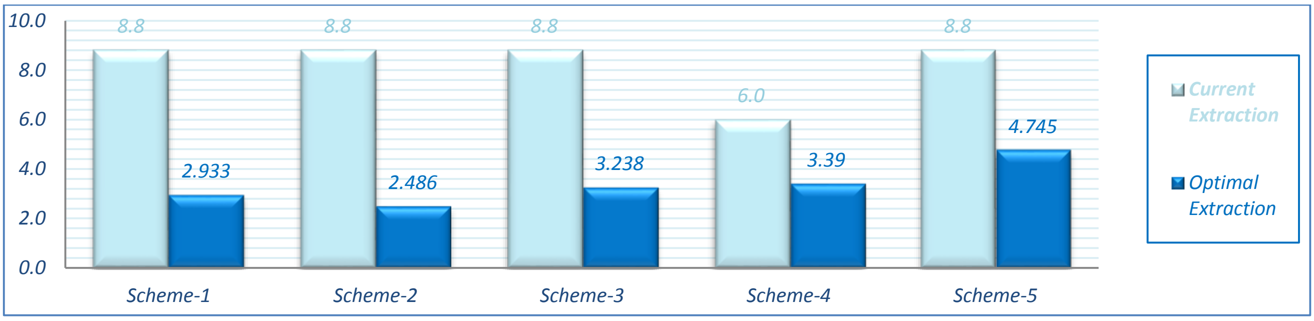

Fig. 14 Comparison among future year (2034) total estimated extractions and optimum solutions of all yearly management schemes (the values x 10^6 m^3/yr).