Integrated Optimization with 3D Variable Density Groundwater Flow and Solute Transport Model to Investigate an Efficient Groundwater Management Scheme in Bangkok Aquifers System

P. Arlai

Abstract— *The study explores seven different groundwater management schemes for the best sustainable future groundwater restoration of the Bangkok aquifers system. The first three are "non-constructive" schemes. In a second part of this article, the study employs, for the first time, a highly complex groundwater management optimization tool, the GWM-model---which uses techniques of linear programming and nonlinear optimization---, to optimize various other recharge- and clean-up well configurations of the best integrated non-constructive and constructive schemes investigated earlier (Arlai et al., 2007) and, in addition, optimizes three new schemes that use a "water supply trade-off concept" for the in-lieu water supply cells of the recharge wells. Next, all seven schemes are re-simulated with the variable-density flow and solute transport model SEAWAT-2000 to see how their efficiency is impacted by saline density effects. Finally, the author is doing a very careful evaluation and comparison of the hydraulic- and the groundwater-quality efficiency and of the total financial costs of all schemes investigated and proposes one of them as the best alternative for realization.*

Keywords— **Groundwater flow and solute transport, optimization technique, variable density effect, groundwater management.**

1. INTRODUCTION

Even though the simultaneously acting two cradles of the major saline pollution in the Bangkok aquifer system have already been clarified and some sustainable aquifer remediation concepts, consisting in both non-constructive and integrating policies & constructive measures have been proposed in Arlai et al., 2006b, the latter may globally not be optimal, neither in terms of hydraulics nor of economics, as they have exclusively been determined by human judgment or so-called "trial & error". Furthermore, the numerical method used there, i.e. MODFLOW-96&MT3DMS, did not yet take into account the density-dependent effects of the saline concentrations on the flow and solute transport. In the present article I will overcome these two limitations partly by

a) application of the groundwater management optimization module GWM (Ahlfeld et al., 2005), which embedded in MODFLOW-2000, to further optimize hydraulically and economically the number of recharge-, clean-up wells and three new water trade-off concepts for the given set of head targets,

b) use of the variable-density model SEAWAT-2000 to investigate the density effects on the optimized schemes proposed in a) and on the non-constructive schemes from a previous paper (Arlai et al., 2007).

It should be noted that this consecutive approach is, theoretically, not completely wishful, as neither the solute transport, nor the density-dependency of the groundwater flow are incorporated a priori in the GWM analysis. Nevertheless it is the best that can be achieved with the modeling resources available at the present time. Given these caveats, I will re-evaluate in the present article the three most efficient non-constructive schemes found earlier in Arlai et al., 2006b by means of the MODFLOW-96 & MT3DMS trial & error simulations and will examine, additionally, 4 more new optimal groundwater schemes, i.e. a total of 7 schemes. These 7 schemes are, namely, the

(1) 1st scheme - the sustainable yield scheme (Arlai et al., 2006a),

(2) 2nd scheme – a non-constructive scheme (the 19th scheme from Arlai et al., 2006b),

(3) 3rd scheme – another non-constructive scheme (the 10th scheme from Arlai et al., 2006b),

(4) 4th scheme–optimizing the number of recharge- and clean-up wells of the best integrated non- and constructive scheme (the 31st scheme from Arlai et al., 2006b),

(5) 5th scheme- applied "water trade-off concept" to the best non-and constructive 4th scheme (new scheme)

(6) 6th scheme– applying "water trade off concept" to the 2nd scheme (new scheme)

(7) 7th scheme– applying "water trade off concept" to the 3rd scheme (new scheme).

The first three schemes are only re-modeled using the variable-density model-SEAWAT-2000 in order to

Phatcharasak Arlai is a lecturer at Program of Civil and Environmental Engineering and the head of Research Unit for Sustainable Water Resources and Environmental Management, Faculty of Science and Technology, Nakhon Pathom Rajabhat University, 85 Malaiman Rd., Muang, Nakhon Pathom, 73000, Thailand. E-mail: hydrologistunik@hotmail.com; Tel. and Fax: +66-34-261065.

reflect more realistically the density-dependent effects on the groundwater movements and saline transport resulting from these schemes. The 4th scheme is directly obtained from applying GWM, to optimize the number of recharge-and clean-up wells which can attain the same head targets from the previous trial&error simulations. The 5th to 7th "water trade off concept" schemes are simulated with GWM to examine the least-cost effective means to raise the water levels along the front of the seawater intrusion up to zero meter (MSL)--- as the modeled 2032 water levels in the productive water bearing units of these previously simulated remediation schemes are below sea level---, either by shutting off the discharge wells or increasing freshwater injection close to the shoreline through in-lieu water supply, in order better restrain seawater intrusion or to reduce the polluted area of the "without scheme". This approach may particularly appeal to the Thai water authorities who are interested in a recharge concept for the Bangkok aquifers system, to prevent further saltwater encroachment. However, as the GWM-model cannot take into account the density-dependent solute transport into the optimization process, these; firstly, optimized schemes 4 to 7 are re-simulated by SEAWAT-2000. Eventually, the best remediation scenario for the Bangkok aquifer system will is extracted from a comparison of these 7 schemes, based on their effectiveness with respect to (1) the saline pollution reduction, (2) the groundwater-use policy to existing groundwater users and, (3) the scheme's implementation and operational costs.

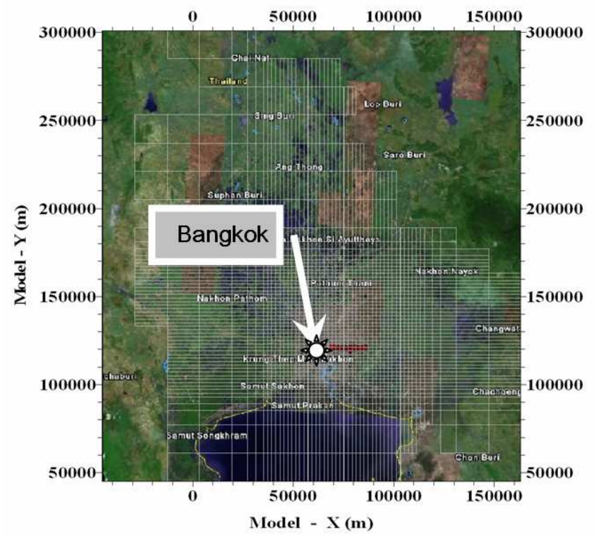
2. STUDY AREA AND MODEL IMPLEMENTATION

Flow Model:

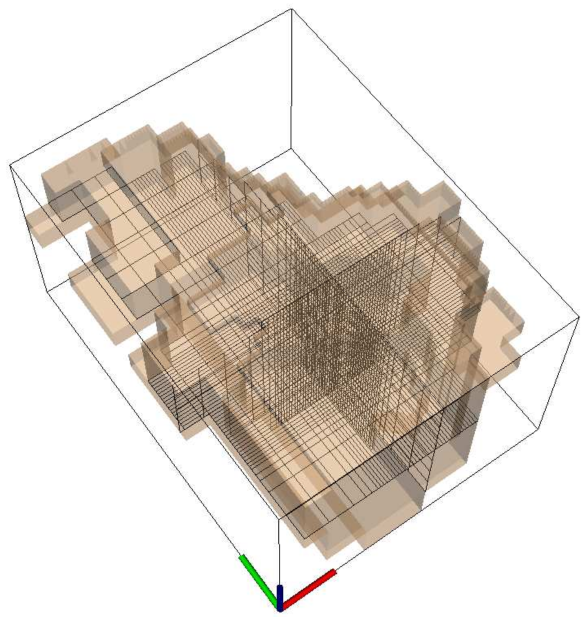
The Bangkok multi-aquifer system is located underneath the lower Chao Praya river basin which is bordered in the east, north and west by ridges of hills and mountains and in the south by the Gulf of Thailand. Hydrogeologically, the aquifers system is conceptualized as 9 layers, i.e., the topmost clay layer and eight lower principle confined aquifers (Arlai et al., 2006a). The groundwater flow model for the Bangkok multilayered aquifers is implemented by the 3D finite-difference model MODFLOW-96 and SEAWAT-2000, with 9 modeled layers whereby the topmost clay layer is treated as an unconfined aquifer and the 8 lower ones as confined aquifers. The model is divided into 55 rows and 52 columns with grid sizes varying from 2*2 km^2 to 16*16 km^2, following the approach of Arlai et al. (2006a) (Fig.1). The top boundary of the model is specified as constant head, representing the water table. The main recharges into the aquifer system are at the outcropping basin flanks and are simulated also as constant head that is set equal to the terrain altitude. Because the topmost clay layer has a thickness that varies from 15 to 30 meters, then recharge rate inside the basin is zero. The bottom of 9th layer is assigned as a NEUMAN boundary. All offshore cells in the uppermost layer are set as Dirichlet BC based on bathymetry is specified. Cells at the southern 55th row of the lower modeled layers that are connected to the Gulf of Thailand are treated as DIRICHLET boundary condition at sea level.

Solute transport model:

Dirichlet constant-concentration BC's for the saline concentrations are set at all active cells for the 1st layer reflecting the upper enriched saline clay layer that acts as a source of saline pollution inland over much of the extent of the model domain. Another intrusion source is the seawater offshore. Here some cells at the 55th row of the 2nd and 3rd layer which intersect the Gulf of Thailand have also been attributed a constant-concentration BC.



(a)



(b)

Fig.1. The FD grid in the 5th layer of the groundwater flow and solute transport model (a), and the 3D FD grid of the 9-multilayered model of Bangkok aquifers system (b).

3. THEORETICAL STATEMENT OF THE GROUNDWATER MANAGEMENT PROBLEM

Linear programming formulation

The ground-water management (GWM) problem is set into a form that can be solved using so-called linear programming techniques. As such the GWM problem consists of a (linear) objective function Z of the decision variables x that is either maximized or minimized, subject to constraints of these decision variables, i.e. (cf. Ahlfeld et al., 2005).

$$\text{Maximize (minimize)} \quad Z = cTx \tag{1}$$

subject to

$$Ax = b \tag{2}$$

and $0 < x < u$ (3)

were Z is the value of the objective function; c is a transposed column vector of objective-function coefficients associated with the decision variables; x is a column vector of decision variables with upper bounds u; A is a matrix of coefficients defining the form of the constraints; and b is a column vector of right-hand-side coefficients associated with the constraints. The constrained linear programming problem (2) to (3) is solved by the well-known Simplex method.

Nonlinear constrained optimization approach

As the topmost modeled layer of the Bangkok aquifer system is fully convertible between a confined and an unconfined aquifer (setting the parameter LAYCON = 3 in MODFLOW), there will be a nonlinear relation between the position of the water table and the discharge- or injection stresses. Thus the constrained optimization problems become nonlinear which is more intricate to handle computationally. The usual approach consists then in linearizing the nonlinear objective function through a Taylor series expansion and to obtain a linear programming problem as above that can be solved as stated by the simplex method. This technique is also called sequential linear programming (SLP).

Formulation of the objective function and the constraints for the Bangkok aquifers GWM problem

According to the goals of the GWM optimization schemes for the Bangkok aquifers explained above, the constrained groundwater management optimization problem is formulated in two ways:

(1) For the optimization of the 4th scheme the objective function is to minimize the rates Q (or costs) of possibly 93 recharge and 93 clean-up well-candidates (Figure 8.1), subject to the constraints that (a) the maximum recharge and extraction well rates Q are less than 12000 CMD, (b) the total recharge rate cannot be greater than the extraction rate and, (c) the computed heads h at 42 spatially- fixed locations along the two lines of the proposed recharge wells and clean-up well barrier in layers 3 to 5 are not dropping below specified values H---- obtained from an earlier MODFLOW calibration of the "non-optimized" well scheme within the Bangkok Aquifers system (Arlai et al., 2006b)--- and that appears to be appropriate to repel future seawater intrusion (cf. Reichard et al., 2003). With these goals the GWM-problem is mathematically stated as follows:

$$Min\left(\sum_{n=1}^{31}\beta_n * (R_{3n} + Q_{3n} + R_{4n} + Q_{4n} + R_{5n} + Q_{5n}) * T_{Qw_n}\right) \tag{4}$$

subject to the constraints

$$\begin{pmatrix} 0 \le R_{kn} \le 12000; k = 3,4,5; n = 1,..,31 \\ 0 \le Q_{kn} \le 12000; k = 3,4,5; n = 1,..,31 \end{pmatrix} \tag{5}$$

$$\left(\sum_{k=3}^{k=5}\cdot\sum_{n=1}^{n=31} R_{kn} \le \sum_{k=3}^{k=5}\cdot\sum_{n=1}^{n=31} Q_{kn}\right) \tag{6}$$

and $h_{i,j,k,2} \ge H_{i,j,k,2}$ ($\sum$ i + j + k = 42) (7)

where R_{kn} is the recharge rate, Q_{kn}, the clean-up (discharge) rate in layer k and well site n (n = 31 is max. number of flux decision variables for layer k); β_n is the cost or benefit per unit volume of water withdrawn or recharged at well site n, (if only flow-rate is optimized, β_n is set to a dimensionless value of 1.0); T_{Qwn} is the total active duration of the flow-rate that is taken here as identical with T_{Qwn} = 7665 days (for the stress period 2 between year 2012 and 2032) at all well sites; is the modeled head at the 42 head constraint locations at col.= i, row = j, layer = k and stress period 2; and is the named head constraint acting as a flow barrier.

(2) For the optimization of the 5th to 7th scheme- the objective function is to minimize the monetary costs βQ of the "water trade-off concept" of possible 93 recharge wells and 123 in- lieu delivered water supply cells ---with the number of recharge wells and in-lieu-delivered water supply cells taken from those cells whose discharge wells have rates are greater than 500 CMD (Fig.2), subject to the constraints that, (a) the maximum recharge and extraction well rates Q are, in turn, equal or less than 12000 CMD, their existing pumping rates of selected discharged cells and, (b) the computed heads h at 42 spatially- head constraints along of the proposed recharge wells in layers 3 to 5 do not decline below specified values H = 0 meter (MSL) and that which appears to be appropriate to avert future seawater invasion (cf. Reichard et al., 2003). By that, the objective function and the constraints can be formulated mathematically as follows:

$$Min\left(\sum_{n_R=1;kn_W=1}^{N_R=31;3N_W=31;4N_W=60;5N_W=32}\left(\beta_R*\left[R_{3n_R}+R_{4n_R}+R_{5n_R}\right]+\beta_W*\left[Q_{3n_W}+Q_{4n_W}+Q_{5n_W}\right]\right)T_{QW_n}\right) \quad (8)$$

subject to the constraints

$$\begin{pmatrix} 0\leq R_{kn}\leq 12000; k=3,4,5; n=1,..,31 \\ 0\leq Q_{kn}\leq Q_{exn}; k=3,4,5; n=31,60,32 \end{pmatrix} \quad (9)$$

$$h_{i,j,k,2}\geq 0 \quad (10)$$

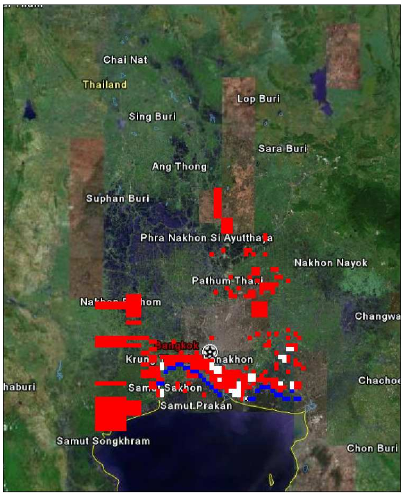
and $(\sum i + j + k = 42)$ (11)

where R_{kn} is the recharge rate, Q_{kn} , the in-lieu delivered water rate cell in layer k and well site n (n = 31 for Rkn and 31, 60, 32 for Q_{kn} are max. number of flux decision variables for layer k=3,4 and 5; βR and βW are the operational recharged- (approximate 0.43 USD; modified from Pyne, 1995) and in-lieu delivered water cost per CMD (approximate 0.4 USD; modified from the Bangkok Metropolitan Water Work Authority; assumed 40 Baht ~ 1 USD) at well site n; T_{Qwn} is the total active duration of the flow-rate that is taken here as identical with T_{Qwn} = 7665 days (for the stress period 2 between year 2012 and 2032) at all well sites; is the modeled head at the 42 head constraint locations at col.= i, row = j, layer = k and stress period 2.

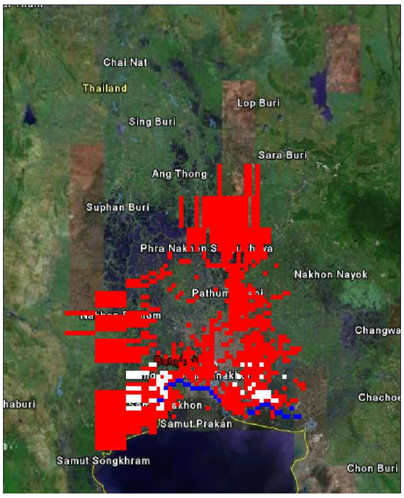
As stated, the GWM problem for the present application is nonlinear, i.e. the hydraulic heads depend in a nonlinear manner on the well-pumping (recharge or discharge). Therefore the problem is solved through SLP, once the head constraints are linearized through 1st - order Taylor series expansion with respect to the flow-rate decision variables (R,Q) as follows:

$$h_{i,j,k,2}(R_{kn}andQ_{kn})=h^{\nu}_{i,j,k,2}(R^{\nu}_{kn}andQ^{\nu}_{kn})$$
$$+\sum_{n=1}^{N}\frac{\partial h^{\nu}_{i,j,k,2}}{\partial(R^{\nu}_{kn}andQ^{\nu}_{kn})}((R^{\nu}_{kn}andQ^{\nu}_{kn}))((R_{kn}orQ_{kn})-(R^{\nu}_{kn}andQ^{\nu}_{kn})) \quad (12)$$

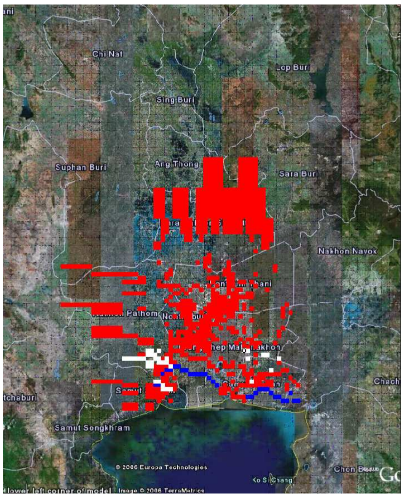
where the superscript ν denotes the iteration level, $h_{i,j,k}$ is the head at col.= i, row = j, layer = k and stress period 2 obtained when the set of withdrawal and in lieu water supply rates $(R^{\nu}_{kn}andQ^{\nu}_{kn})$ is applied, $(R_{kn}andQ_{kn})$ is the new set of withdrawal and in lieu water supply rates and $\frac{\partial h^{\nu}_{i,j,k,2}}{\partial(R^{\nu}_{kn}andQ^{\nu}_{kn})}$ are the response coefficients. The SLP algorithm recalculates the response coefficient for the heads at each iteration ν from a new set of optimal withdrawal- and in-lieu water supply rates which are obtained from the linear programming solution of the previous iteration using the simplex algorithm.



(a)



(b)



(c)

Fig. 2. An example of in lieu delivered water supply cell-(white cell), recharge well (blue cell) candidates and withdrawal cells (orange cell) in layer 3 (a), 4(b) and 5 (c) of the scheme 5 to 7.

4. DISCUSSION OF THE VARIOUS GROUND-WATER MANAGEMENT SCHEMES

As mentioned 7 schemes will be evaluated in this chapter, and for practical purposes, are to be compared to the reference scheme, the so-called "laissez-faire" scheme (Arlai et al., 2006b).

4.1 1st scheme - sustainable yield

The sustainable yield is defined as "the maximal groundwater yield that may be withdrawn so that the water levels in the third, forth and fifth layer do not decrease by more than 25% of their current water levels (Dec, 2002)". This scheme constrained pumping in the 6th to 9th aquifer by projecting into the future for the next 30 years (2003 to 2032) the acceleration rate of pumping from 1983 to 2002. Finally, the sustainability condition for the above conditions can be met if the pumping in layers 3, 4 and 5 is to be decreased at the rate of 1.2%, 1.2% and 1.9% per year, respectively (Arlai et al., 2006a).

4.2 2nd scheme -non-constructive scheme

It consists in keeping the present pump rate (2002) in each layer from 2012 to 2032, but decrease the pumping thereafter to 60% of today in low-sensitive zones and shut off completely the pumps in high-sensitive zones. This scheme is allowed to give 5 more years for law enactment.

4.3 3rd scheme - non-constructive scheme

It comprises maintaining the pump rates in layers 3 and 4 at the same rates than those of the WOS scheme from 2012 to 2032, as they are the main aquifer layers exploited, but completely stopping groundwater pumping in layers 5 to 9 which should retard vertical sinking mechanism of the salt plume from the upper source layers. This pump-shutoff in the lower layers will be executed from 2012 to 2032, leaving 5 more years for legal enactment.

4.4 4th scheme - optimized integrated non- and constructive scheme

The scheme is to minimize the least cost of "trial & error" integrated non- and constructive management scheme which combines recharge, clean-up wells and a cease of groundwater pumping in the 6th modeled layer. 31 recharge wells and 31 clean wells along the tongue of seawater intrusion in each layer are specified, resulting in a total of 93 recharge- and 93 clean-up wells (Figure 8.3) in order to attain the heads at the 42 head constraint locations with a complete cease of the groundwater withdrawal in layer 6, and keeping the extraction rates in layers 7 to 9 at the present-day rate (2002). The scheme will be operated from 2012 to 2032 leaving 5 years for realization.

4.5 5th scheme- applied "water trade-off concept" to the integrated non-and constructive scheme (4th scheme)

This scheme is to optimize the "water trade off concept": 93 recharge wells and 123 in-lieu delivered water supply cells candidates are applied (with no clean-up wells) and keeping the 21 head constraints equal to zero meter height (MSL) at the end of 2032. The in-lieu delivered water supply cells are selected from those pumping cells located closed to the shoreline (UTM Y: 694000 to 720000) that have the pump rates in a FD-cell 500 CMD---as the author has tested and found that if the existing pumping rates in a cell are specified to less than 500 CMD, the dimension of the optimized problem becomes too huge to be treated computationally in an acceptable time---. The GWM-optimization of this scheme is to ensure least costs for construction, operation and maintenance for its realization. This optimized scheme operates from 2012 to 2032, allowing 5 more years for governmental ruling (Fig.2.).

4.6 6th-scheme- applying "water trade off concept" to the 2nd scheme

It applies the "water trade off concept" as described in the 5th scheme with the 2^{nd} scheme.

4.7 7^{th}-scheme- appliying "water trade off concept" to the 3^{rd} scheme

It applies the "water trade off concept" in 5^{th} scheme with the 3^{rd} scheme.

5. RESULTS

5.1 Optimization results for the 4th scheme

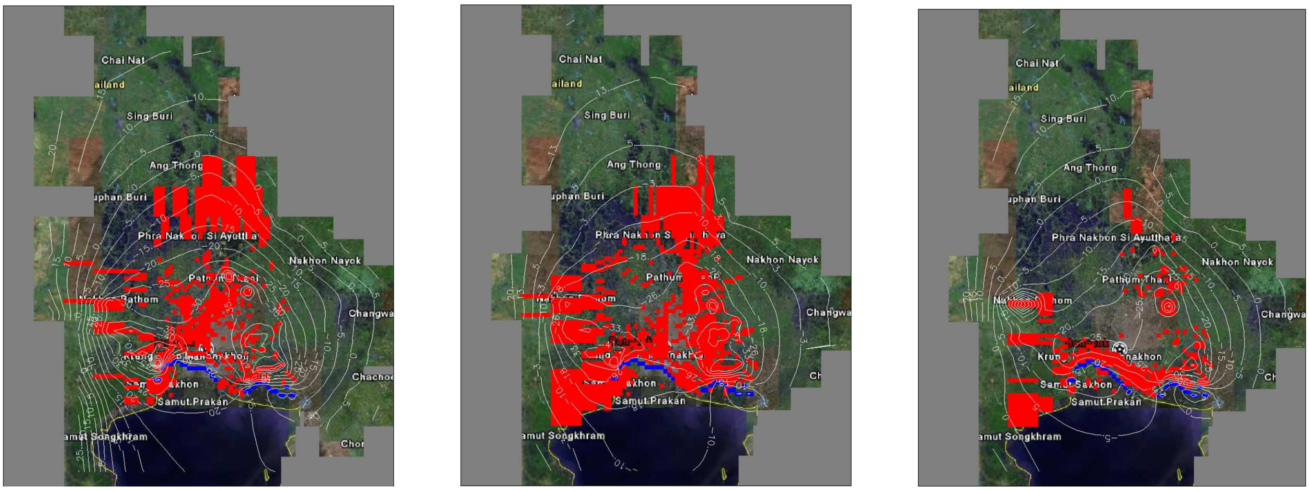
For the "trial & error" well scheme which combines recharge, clean-up wells and a cease of groundwater pumping in the 6th modeled layer, 31 recharge wells and 31 clean wells along the tongue of seawater intrusion in each layer are specified, resulting in a total of 93 recharge- and 93 clean-up wells (Fig.3). Each of these wells is operated at a rate of 7000 CMD. Hence the total water circulation rate in this scenario is $6.51*10^5$ CMD. On the other hand, using the MODFLOW-GWM optimization code to solve the GMW-objective function and constraints, results in a total of only 37 recharge-(15, 10, 12 wells in layer 3, 4 and 5) and 27 clean-up (16, 6, 5 wells in layer 3, 4 and 5) wells to control the heads at the 42 head constraint locations. And the water circulation rate is merely $3.17*10^5$ CMD. Hence, compared with the "trial & error" well scheme, the MODFLOW-GWM "optimized" scenario results in a significant reduction in both the number of wells and total water circulation rate (a 51% reduction), i.e., obviously a tremendous cost-saving, as discussed below.

Fig.4. illustrates that the modeled heads for year 2032 of the "trial & error"- and "optimized" well schemes coincide pretty well at the locations of the head constraints—but less so in the seaward zone where the named water circulation rate differences are prevalent, with the effect that the "trial & error"- computed heads in the gulf area are higher than those of the "optimized" one (Fig.4.). The minimum head recoveries in 2032 for

the two schemes are listed in Table 1. One notes that the head recovery for the "optimized" scenario is better than that of the "trial & error" one which is due to the fact that some of the, evidently redundant clean-up wells of this somewhat arbitrary scenario have a detrimental effect on the head recovery. Table 1 lists also the economic benefits of employing the "optimized" instead of the "trial & error" – scheme---the former being calculated by associating a unit price in the objective function (4)---. One clearly observes that, not only is the "optimized" well scheme cheaper by 154 million US Dollars for the project implementation, it results also in annual operation and maintenance cost savings of 76.7 million US Dollar compared to the latter scheme.

5.2 Optimization results for the 5th to 7th schemes

Table 2 lists the optimization results obtained for three new schemes (5^{th}-7^{th} scheme), namely, the cell candidates for the recharge-wells and the in-lieu delivered water supply wells which are able to recover the piezometric heads up to the constraints of zero meter (MSL), and the least costs achieved. The table illustrates that the 7th scheme is the most effective, at least with regard to the costs of installation and operation of the recharge wells, as both the number of recharge wells and the recharge rates are at a minimum while satisfying the zero meter (MSL) head constraint as a water barrier layers 3 to 5. However, at this current stage, it cannot be concluded that this is really best scheme, since, in principle, for each optimized recharge well and in-lieu delivered water supply cell configuration the models should be re-simulated using SEAWAT-2000 to check for possible solute density effects on the schemes' groundwater flow effectiveness, neglected so far.



(a) (b) (c)

Fig. 3. Trial-and error well scheme: Orange area shows the distribution of the present day pumps, blue area the line of recharge wells, with the clean-up wells located 4 cells northward of the former.

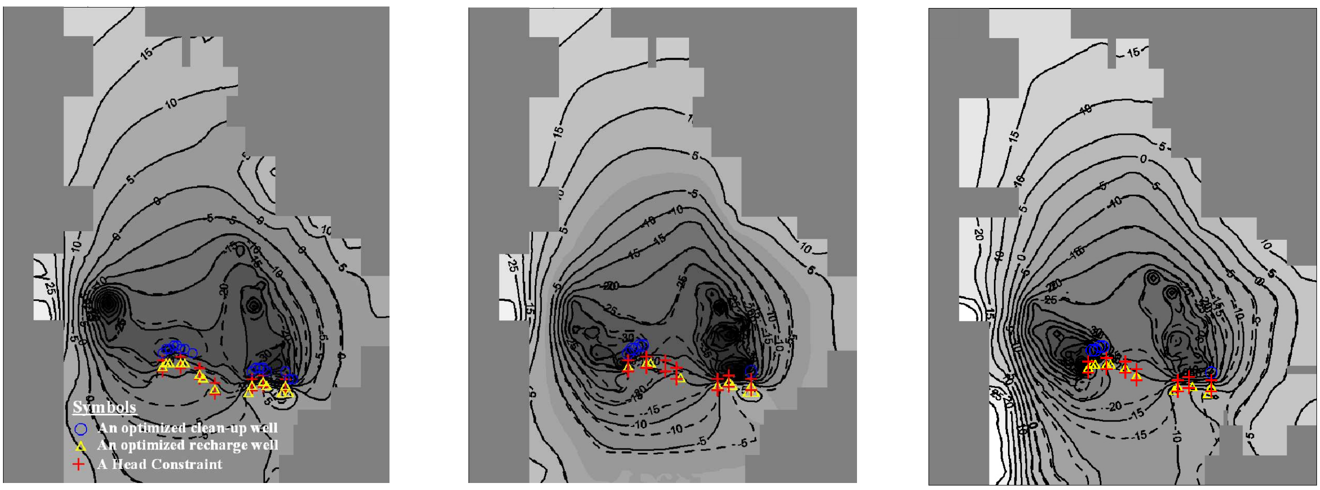


Fig. 4. 2032-heads for the "trial & error"- (solid lines) and "optimized" (dashed lines) well scheme in layers 3(a), 4(b) and 5(c); a blue circle is an optimized clean-up well, a yellow triangle is an optimized recharge well, a red plus is a head constraint.

Table 1. Comparison of head recovery and values of cost-function (hydraulic costs) and monetary costs for implementation and operational & maintenance for the two restoration schemes proposed.

Aspect	Original well scheme						Optimized well scheme						
	Layer3	Layer4	Layer5	Layer6	Layer7	Total	Layer3	Layer4	Layer5	Layer6	Layer7	Total	% Saving
1.Head recovery													
a.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
b.	-54.79	-64.82	-82.26	-31.19	-28.56	-82.26	-55.00	-59.66	-67.82	-31.61	-28.06	-67.82	
2.Cost													
a.	31	31	31			93	15	10	12			37	60
b.	31	31	31			93	16	6	5			27	71
c.	2.17	2.17	2.17			6.51	1.45	0.87	0.85			3.17	51
d.	2.17	2.17	2.17			6.51	1.85	0.72	0.60			3.17	51
e.	100	100	100			300	77	36	33			146	51
f.	49.90	49.90	49.90			149.70	36.37	18.94	17.69			73.00	51

Remark

Unit Cost of recharge project implementation 210 US Dollar/CMD, cf. Pyne, 1995

Unit Cost of clean-up project implementation 251 US Dollar/CMD,cf.Henthorne,2003

Unit Cost of O&M of recharge project 0.43 US Dollar/CMD,cf.Reichard et al., 2003

Unit Cost of O&M of clean-up project 0.2 US Dollar/CMD,cf.Henthorne,2003

1.Piezometric head recovery
- a.Similarity along the head constraints
- b.Minimum head (m. MSL)

2.Cost
- a.Number of recharge well
- b.Number of clean-up well
- c.Total recharge rate (10^5 CMD)
- d.Total clean-up rate (10^5 CMD)
- e.Project implementation cost (Million US$)
- f.Operational&Maintenance Cost/year (Million US$)

Table 2. Summary of optimization results for the 5th to 7th scheme

Scheme	Recharged well candidates	In lieu well cells candidates	Optimized recharged wells			Optimized in lieu delivered water supply		
			Number of wells	Total recharge rate (CMD)	Annual operational cost (10^6 USD)	Number of cells	Total in lieu delivered water supply rate (CMD)	Annual operational cost (10^6 USD)
5th	93	123	30	229035	36	123	2.42E5	38
6th	93	123	30	163612	26	123	2.42E5	38
7th	93	123	23	160570	25	123	2.42E5	38

5.3 Quantitative analysis of variable-density effect of all schemes

As the GWM-MODFLOW-2000 module could no simulate the density-dependent groundwater flow and solute transport, the WOS-scheme and all other schemes will be re-run using SEAWAT-2000. The most salient results obtained in this manner---with respect to those of the WOS-scheme---are summarized in terms of groundwater hydraulics, -quantity and –quality for layers 3 to 8 of the aquifer in Fig.5. The vertical saline plume pollution- and horizontal seawater intrusion extent in Fig.5. are, in turn, defined as that contaminated area where the salinity concentrations are higher than 250 and 4000 mg/l-locates nearby/closed to shoreline, with the reduction measured relative to original polluted area of the WOS-scheme. The % head recovery is specified by the ratio of the minimum head of each scheme to that of the WOS- scheme. The diagram shows that the 6th scheme is clearly the best one to reclaim both the piezometric heads and the groundwater quality, in as much as the average head recovery is 68%, and the area polluted by vertical saline plume intrusion is reduced by 9 % and that affected by horizontal seawater intrusion by 18%. Not surprisingly, all the 5th to 7th --- the “water trade off concept” schemes--- reduce both polluted areas better and result in better head recoveries than all other schemes.

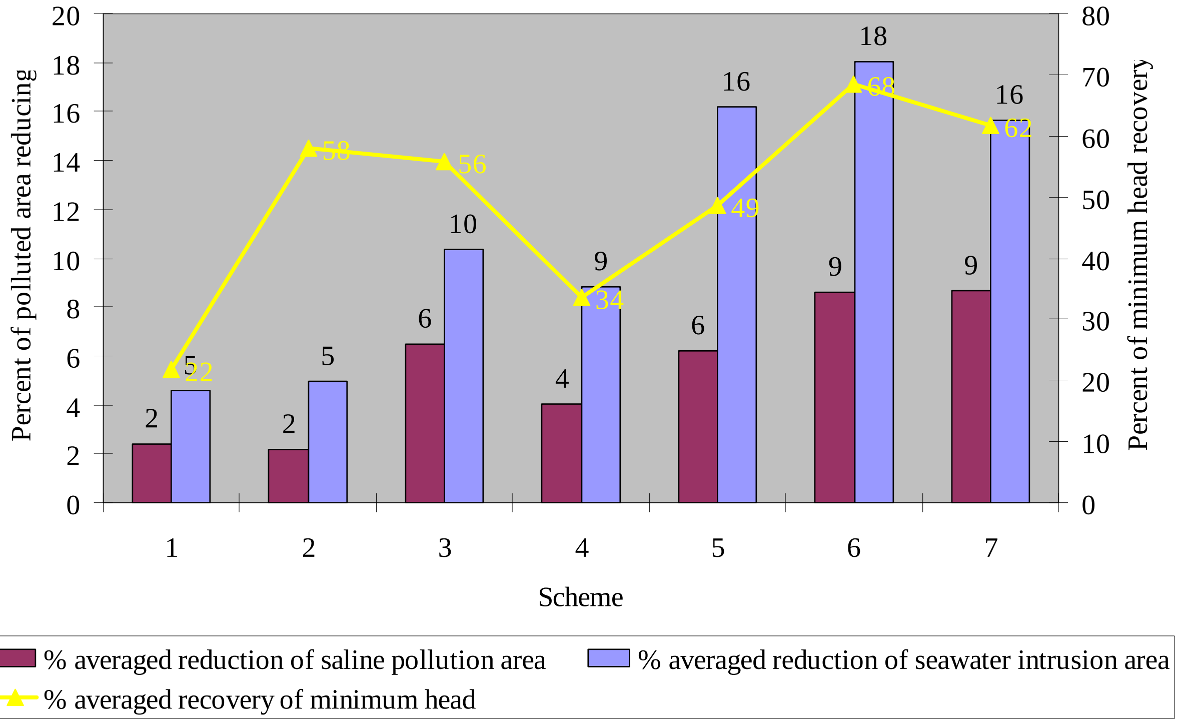


Fig.5. Summary of % averaged reduction of vertical saline plume pollution area, - seawater intrusion area and head recovery in layers 3 to 8 relative to the WOS scheme.

5.4 Detailed cost-analysis of the various schemes

The schemes discussed can be divided into three categories, namely, (a) non-constructive schemes- 1st to 3rd scheme, (b), optimized non-and constructive scheme-4th scheme and (c) applied water trade off scheme-5th to 7th scheme. For the category (a) schemes, the unmet water demand (umd) and which is defined as the difference between the total withdrawal rate difference between the WOS-scheme and the pumping rate under the policy of that scheme is assumed to be served by surface water supply from Bangkok Metropolitan Water Authority (BMWA). Hence, the costs for the non-constructive scheme must be estimated by taking into account the construction costs of the delivering water supply pipe, connected to a water supply distributor station of BMWA, i.e. construction costs of a 8 inch diameter – pipe, 20 meters long are 5350 USD (including 7% VAT) which can provides water supply 934 CMD (assuming flow velocity in a pipe 1 m/s and operating 8 hrs/day), meanwhile the costs for the use of the additional water supplied are assumed to be covered by existing groundwater users there, namely 0.4 USD for a cubic meter of water supplied (BMWA- service rate and assuming 1 USD ~ 40 Baht).

These assumptions apply also for the unmet demand of the other two scheme-categories. The costs of scheme-category (b) are taken from Arlai et al. (2007). The costs of the scheme-category (c) are determined by calculating the implementation as well as the operational expenses for the recharge wells using the values of (Arlai et al., 2007), while the costs of the in-lieu water supply is taking into account only the costs of delivering water pipe construction as stated above. The total costs are then defined as the sum of the initial costs of implementation plus annual operational cost in the target year 2032. The cost summary of Table 3 unveils that the sustainable yield-scheme requires the smallest investment among all the other schemes, namely 2.22 million USD, while the investment costs of the 7th scheme are the lowest among the group of integrated non- and constructive schemes, i.e. 65 million USD. One an interesting point to mention is that the 6th scheme---which has been the best with respect to the efficiency in recovering the groundwater heads and the – quality--- requires only one million USD more than the 7th scheme. On the other hand, if the schemes's impact on the groundwater use policy is taken into account, one must consider also the unmet water demand (umd), since a higher umd would be more affecting existing groundwater users. From this point of view, the 4th scheme would be the least painful for them.

6. DISCUSSION

From the results obtained, it is difficult to give a clear "cut" for the best aquifer restoration scheme when considering the recovery of the groundwater quality, the costs of implementation & operation, and the impact of the groundwater use policy of each scheme on the existing groundwater users. As a trade-off and possible guidance to the water authorities of Thailand to choose among the various options proposed, these three relevant parameters, i.e. reduction of total pollution area, total cost and unmet water demand of each scheme are plotted in Fig.6.

Table 3. Summary of costs in each scheme.

Scheme	Unmet water Demand 10^6CMD	Cost of water supply implementation for unmet demand in 2032 Million USD	Cost of Recharge wells Implementation in 2032 Million USD	Annual Operational cost of Recharge well in 2032 Million USD	Total Cost in 2032 Million USD
1	0.39	2.22			2.22
2	0.86	4.91			4.91
3	0.88	5.02			5.02
4	0.16	0.94	146	73	220
5	0.72	4.14	48	36	88
6	1.00	5.74	34	26	66
7	1.00	5.73	34	25	65

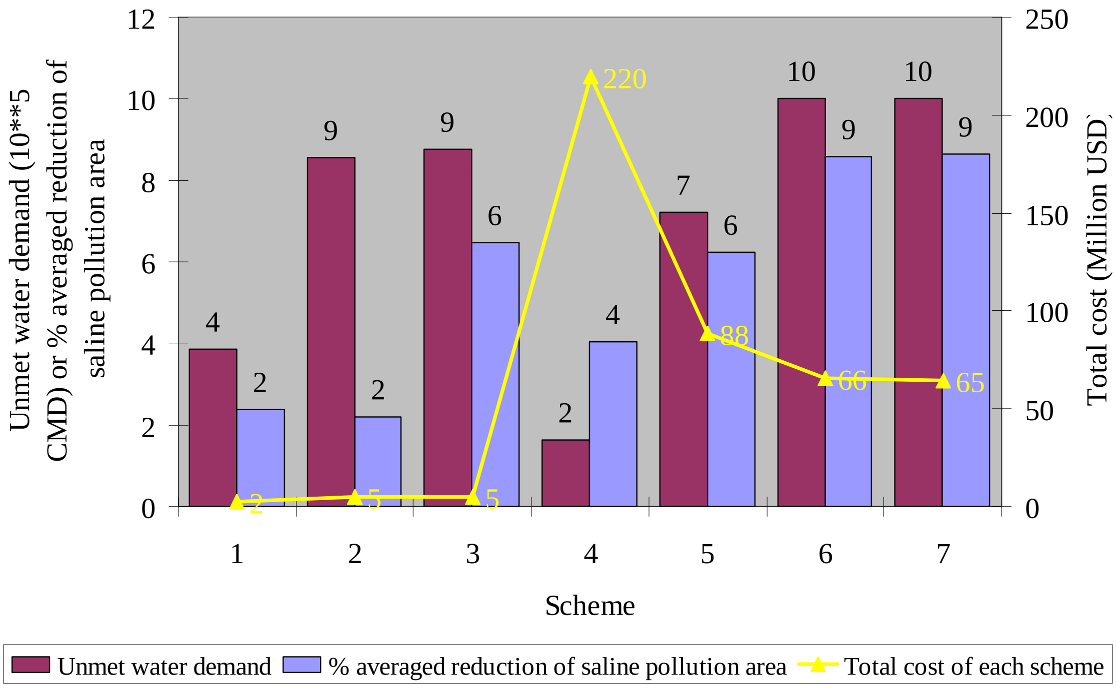
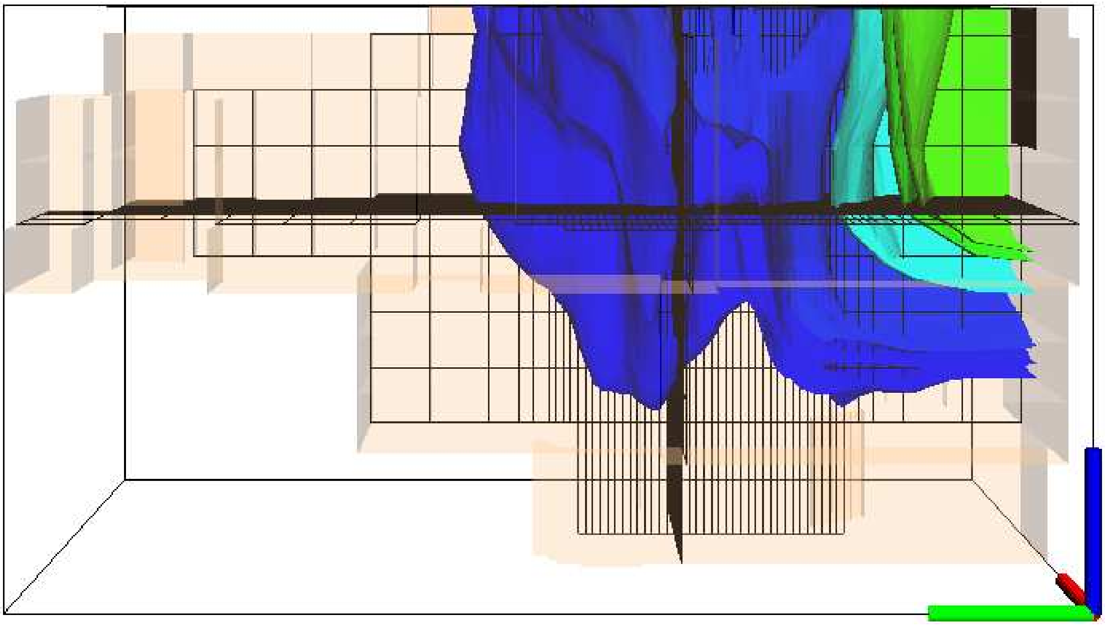
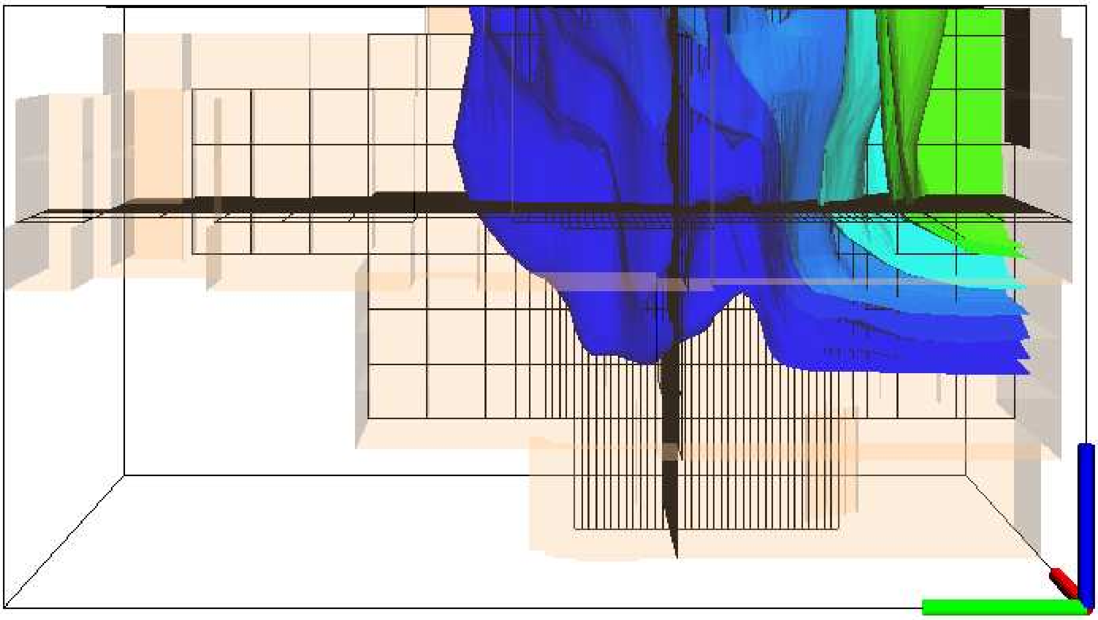


Fig.6. Comparison of unmet water demand, averaged reduction of saline pollution area and total costs of each scheme.

Fig.6. discloses that the 3rd scheme appears to be the optimal one for sustainable groundwater management and restoration of the Bangkok aquifers system. This is because the 3rd scheme can not only reclaim the total saline pollution area up to about two third of that of the best schemes---the 6th and 7th scheme--- and also retard the vertical sinking of the salinity plume from the upper marine clay layers (as shown in Fig.7), but it also requires also an investment of only 5.02 million USD for construction costs which is 92% cheaper than the total costs of the 6th and 7th scheme. Even this 3rd scheme may considerably impact the existing groundwater users, they latter may get a compensation from the construction costs saved of the water supply pipe connecting to the BMWA distributor and may thus pay only the unit costs of the water used.



(a)



(b)

Fig.7. Saline concentration profile (UTM-X = 662000 m.) of the WOS-scheme (a) and the 3rd scheme (b) located at the western side of the Chao Praya river, concentrations in kg/m^3.

7. SUMMARY

Seven different groundwater management schemes are investigated for the best sustainable future groundwater restoration of the Bangkok aquifers system. The first three non-constructive schemes that have been selected from a previous paper where they have been simulated only by the constant-density groundwater flow and solute transport model MODFLOW-96&MT3DMS (Arlai et al., 2006a and b) are re-run by the newest version of the variable density groundwater flow and solute transport model-SEAWAT-2000, allowing for a more realistic determination of the flow and saline transport due these schemes. The 4th scheme is set-up by applying GWM-optimized recharge- and clean-up wells to the best non-constructive scheme investigated earlier, and the 5th, 6th and 7th scheme uses also GWM to optimize "the water supply trade-off concept" with the 4th, 2nd and 3rd scheme, respectively. After optimizing the 4th to 7th scheme, the optimal non-and constructive- and the in-lieu water supply concept schemes are re-simulated with the variable-density flow and solute transport model SEAWAT-2000. Next, the hydraulic- and the groundwater-quality efficiency and the total financial costs of all schemes are evaluated and compared. Eventually, the 3rd scheme appears to be the optimal scheme in all points of views and it is the one that may be recommended to the Thai water resources authorities for possible realization.

ACKNOWLEDGMENT

I cordially express my special thanks to Prof.Dr.rer.nat Manfred Koch who has kindly supervised me to pursue my Dr.-Ing dissertation and my friends at Department of Geohydraulic and Engineering Hydrology, Faculty of Civil Engineering, University of Kassel, Republic of Germany.

REFERENCES

[1] Ahlfeld, D.P, P.M. Barlow, and A.E. Mulligan (2005), GWM A Ground-water Management Process for the U.S. Geological Survey Modular Ground-Water Model (MODFLOW-2000), USGS Open-File Report 2005-1072, 124p.

[2] Arlai, P., Koch, M. and Koontanakulvong, S. 2006, Modeling flow and transport for sustainable yield estimation of groundwater resources in the Bangkok aquifer system, EGU General Assembly 2006, Vienna, Austria, 2-7 April.

[3] Arlai, P., Koch, M., Koontanakulvong, S. and Weerapol, B. 2006b. Numerical Modeling as a Tool to Investigate the Feasibility of Artificial Recharge to Prevent Possible Saltwater Intrusion into the Bangkok Coastal Aquifers System. In *Proceedings of "Groundwater Hydraulics in Complex Environments"*, Toulouse, France, 12-14 June.

[4] Arlai, P., Koch, M. and Koontanakulvong, S. 2006. Statistical and Stochastic Approaches to Assess Reasonable Calibrated Parameters in a Complex Multi-Aquifer System. In *Proceedings of "CMWR XVI-Computational Methods in Water Resources"*, Copenhagen, Denmark, 19-22 June.

[5] Arlai, P., Koch, M. and Koontanakulvong, S. 2006. Investigation of the Cradle of Saline Contamination and Effective Remediation Schemes for Amending Saline Water Pollution Problem in the Bangkok Coastal Aquifers System. *3rd APHW Conference*, Bangkok, October 16-18, Poster.

[6] Arlai, P., Koch, M. and Koontanakulvong, S. 2007. Embedding an Optimization Module within a 3D Density Dependent Groundwater and Solute Transport Model to determine an effective Groundwater Management Scheme in the Bangkok Aquifers System. *Asian Simulation Modeling 2007*, Chaing Mai, Thailand, January 9-11.

[7] Kogyo, K. 1995. The study on management of groundwater and land subsidence in the Bangkok metropolitan area and its vicinity. Final report, Presented to Department of Mineral Resources, Ministry of Industry and Department of Public Works, Ministry of Interior of the Kingdom of Thailand.

[8] Langevin, C.D., Shoemaker W.B. and Guo, W. 2003. Documentation of SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS transport process (IMT). USGS report 03-426.

[9] Reichard, E.G. et al. 2003. Geohydrology, Geochemistry, and Groundwater Simulation-Optimization of the Central and West Coast Basins, Los Angeles County, California, U.S. Geological Survey Open-File Report 03-4065, 184p.

[10] Sanford, W.E. and Buapeng, S. 1996. Assessment of a Groundwater Flow Model of the Bangkok Basin, Thailand, Using Carbon-14-Based Ages and Paleohydrology, Hydrogeology Journal, v.4, no.4.