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A SIMULATION/OPTIMIZATION APPROACH TO MANAGE GROUNDWATER RESOURCES IN THE GAZA AQUIFER (PALESTINE)

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Summary. A decision support system based on a simulation/optimization approach has been developed and applied to the Gaza Strip coastal aquifer (Palestine) to manage sustainable aquifer development under effective recharge operations and water quality constraints. The paper describes model development and simulation results.

Key words: water resources management, simulation/optimization, genetic algorithm, density-dependent groundwater models, seawater intrusion.

1 INTRODUCTION

Gaza aquifer is the main source of water for supplying agriculture, domestic, and industrial purposes in Gaza Strip. Recently, the rapid increase on water demand to fulfill the needs of the continuous population growth made the aquifer overexploited, leading to huge crises of water scarcity and seawater intrusion. To relieve and narrow the huge deficit between water demand and supply, the use of artificial resources, such as stormwater and reclaimed wastewater[1,2], has been investigated. To manage sustainable aquifer development under effective recharge operations and water quality constraints, a decision support system based on a simulation/optimization (S/O) approach has been developed and applied to the Gaza Strip coastal aquifer system.

2 STUDY AREA

The study is based on previous modeling studies[3,4,5,6], introducing for the first time the reconstruction of the real 3D geometry of the aquifer system. The model area falls within Gaza Strip boundaries and is located to the north-west of the Wadi Gaza (Figure 1). The S/O model is applied to a square area of 2000m side-length parallel to the coastline. The domain surface is discretized into 3,160 triangles and 1,637 nodes with higher density of mesh nodes close to wells (Figure 1). The final grid is built from the layer-by-layer replication of the 2D triangulation following the aquifer stratigraphy. The 3D mesh of the aquifer system is made of 13,096 nodes and 25,280 tetrahedras.

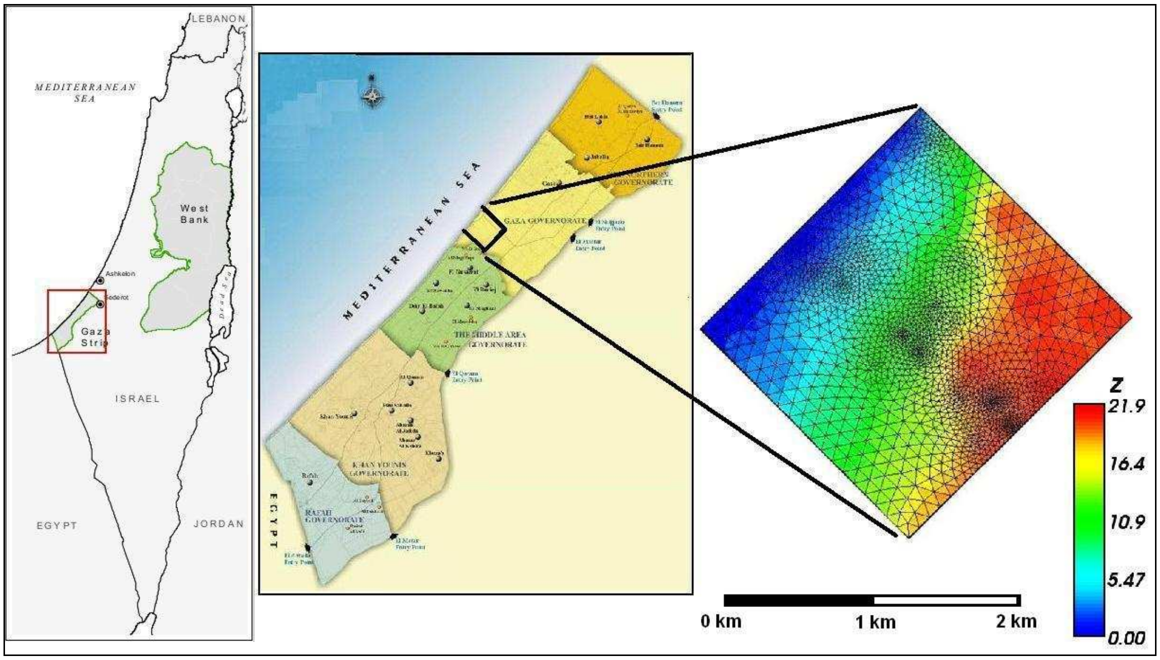

Figure 1. Location of the Gaza Strip (left) and mesh of the study area with the topographic map (right).

Based on the schematic vertical cross section shown Figure 2, the system is discretized into 7 layers, 4 of which are sub-aquifers: A, B1, B2, and C. The top sub-aquifer A (unit 1) is phreatic, whereas sub-aquifers B1 (unit3), B2 (unit5) and C (unit7) become increasingly confined towards the sea. The layers between sub-aquifers are aquitards (units 2, 4, and 6). Horizontal zoning of the aquifer is applied in three areas, according to the soil map (Figure 2).

Parameter	Aquifers			Aquitards
	Sandy regosols	Sandy loess	Dark brown sandy loess	Clay
Saturated hydraulic conductivity in the horizontal direction, m/s	$9 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-6}$
Saturated hydraulic conductivity in the vertical direction, m/s	$9 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-6}$
Longitudinal dispersivity, m	50	50	50	50
Transversal dispersivity, m	10	10	10	10
Effective porosity, /	0.34	0.34	0.34	0.5
Recharge rate, m/s	$6.8 \cdot 10^{-8}$	$2.9 \cdot 10^{-9}$	$2.4 \cdot 10^{-10}$	0
Lateral freshwater flux, m^3/s	$7.6 \cdot 10^{-2}$	$7.6 \cdot 10^{-2}$	$7.6 \cdot 10^{-2}$	$7.6 \cdot 10^{-2}$

Table 1. Parameters and BCs of the simulation model.

The boundary conditions (BC) of the aquifer bottom are set to Neumann-type of no-flux as sealed from the sea[3], while the aquifer top is a recharge boundary by the direct infiltration. The NE and SW boundaries are approximated as zero-flux borders when regarded as groundwater divides with flow lines perpendicular to the coastline[3]. Dirichlet-type of BCs are assigned to the residual parts of the NW (sea side) while the SE boundary (inland side) is subject to Neumann-type constant freshwater inflow. At the sea side, the aquifer system is in contact with the seawater body at the reference salt concentration of 25 grams/liter (C_{max}). Table 1 summarizes the main aquifer hydrogeological parameters and BCs.

Sixteen pumping wells are exploited in the area with variable depths (30-56 m) for municipal and agricultural purposes with a total abstraction of 1.8 Mm^3/year. Figure 2 shows their locations, and classify them according to three different injection configurations used in the recharge scenarios.

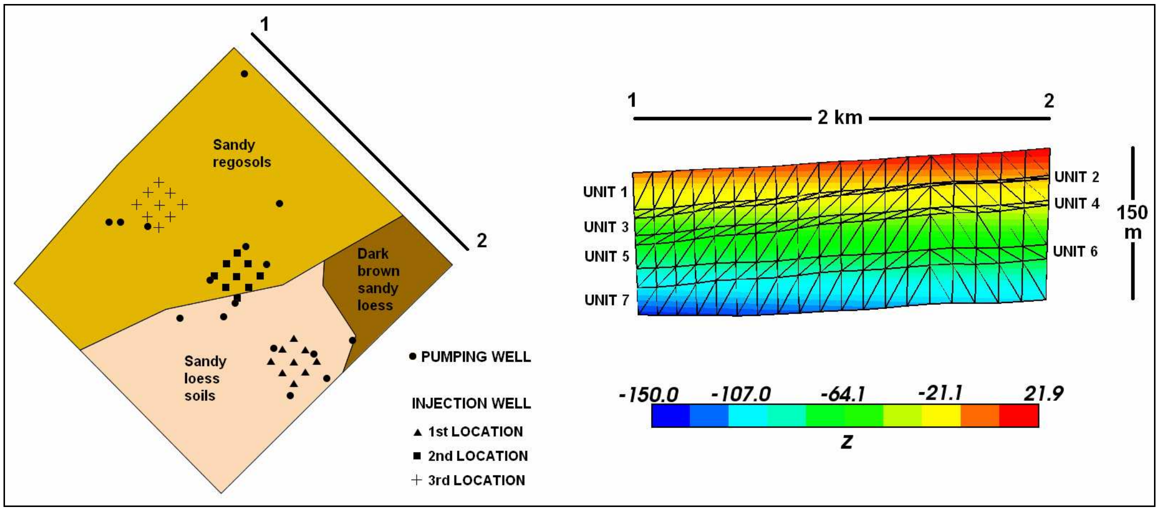

Figure 2. Soil map (left) and vertical cross section of study area (right) with the elevation map. The location of the three recharge configurations (1, 2, 3) is also shown (left).

3 SIMULATION/OPTIMIZATION APPROACH

Groundwater simulation models have been linked with optimization techniques in a single framework to overcome the weakness of using simulation or optimization alone.
However, incorporation of the simulation model within an optimization model is very complex, difficult and strictly problem-oriented. In addition, embedded models become dimensionally too large for a desktop computer, and higher resolution along the spatial and temporal scales may be impossible even for large cluster of interconnected PCs. As an alternative, it is possible to couple a simulation model with a general purpose optimization-based management tool using the simulation/optimization (S/O) approach.[7,8,9,10] In this study the S/O approach is based on the density-dependent variably saturated groundwater flow and salt transport CODESA-3D model[11] and the Carroll's FORTRAN Genetic Algorithm (GA) Driver.[12]

The complete application dataset is available on the Grid computing platform http://grida3.crs4.it. Registered users are allowed to perform, using the AQUAGRID suite of computational services, complex hydrogeological simulations using a high-end computer cluster, via a user-friendly Web gateway[13]. The platform also integrates GIS and 3D visualization services.

Number of wells	Pumping weight w_1	Salinity weight w_2	Individual lenght	Population size	Max population size	Crossover probability	Creep mutation probability
16	1	1-200	96	5	200	0.5	0.0234

Table 2. Parameters of the optimization model.

4 OPTIMIZATION MODEL AND SIMULATION RESULTS

Management of coastal aquifers often requires consideration of multiple objectives[3]. In this study the optimization model considers two conflicting objectives: maximizing pumping rates from the aquifer wells while limiting the salinity of the water withdrawn. A weighted sum[3] is used to incorporate the two objectives into a single scalar objective function, subjected to constraints. The resulting optimization model reads:

$$Max\ Z = w_1 \sum_{i=1}^{n} Q_i - w_2 \sum_{i=1}^{n} Q_i C_i \qquad (1)$$

where i = 1,..., 16, is the well index, w_1 and w_2 are the sum weights, and the design variables Q_i and C_i represent the discharge rate and the salt concentration at the *i-th* well, respectively. Constraints to equation (1) are: $0 \le Q_i \le Q_{\max}$, with the maximum discharge given by the aquifer safe yield divided by the number of pumping wells (Q_{max}=0.00395 m^3/s) and $0 \le C_i \le C_{\max}$ (Table 2). Constraints are automatically satisfied by definition of population space in GA model, whose parameters (as recommended by Carroll[12]) are summarized in Table 2. Set the pumping weight w_1 equal to 1, the model was run 8 times with different w_2 values (1-200) in order to estimate the optimal salinity weighting parameter w_2. As depicted in the trade-off curve between total pumping and total salt mass extracted shown Figure 3, the optimal value of w_2 was found equal to 25, ensuring maximum pumping and total salt mass extracted within the reasonable limits of the feasibility region. After model setup and initialization, two transient management scenarios were simulated for a 1-year time interval. A single S/O run spent an average CPU time of 4 hours on a dual CPU quad core 2.8 GHz system.

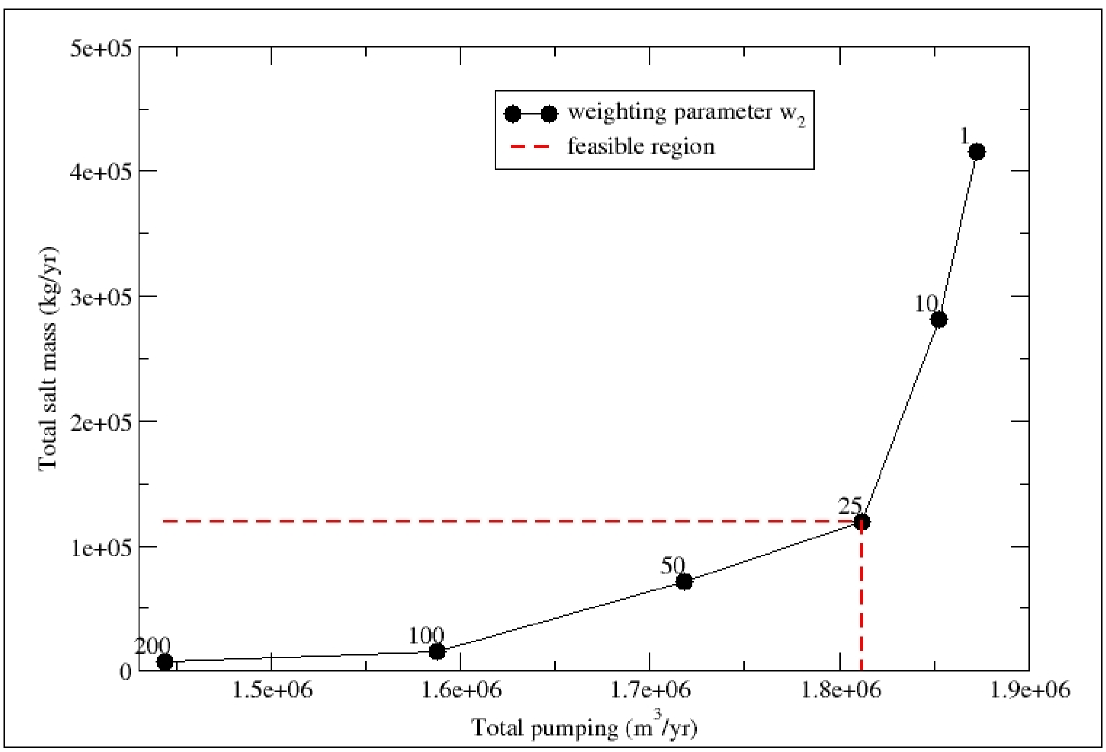

Figure 3. Trade-off curve between total pumping and total salt mass extracted, delimiting a feasible pumping region under the problem constraints.

4.1 Management model 1 (without recharge)

The first management model is based on the objective function of equation (1) in absence of artificial recharge. Table 3 shows the comparison between the optimal pumping strategy (GA) with the non-optimized condition (sim0) for the wells of the study area. The analysis is conducted in terms of design and state variables, namely: discharge (Q, m^3/yr), hydraulic head (h, m), salt normalized concentration (c, /) and total salt mass extracted (S, kg/year) at the wells. The optimum pumping strategy ensures a decrease of 65% in the total extracted salt mass and a recovery of 9% in the hydraulic heads, while allowing to withdrawal the 99% of actual abstraction rates (Table 4). Spatial distribution of heads for the two scenarios is also shown in Figure 4.

Well id	Q (m^3/yr)		h (m)		c (/)		S (kg/yr)	
	Sim0	GA	Sim0	GA	Sim0	GA	Sim0	GA
1	113400	6314	1.30	1.60	0.10484	0.10022	297222	15820
2	108001	120078	1.23	1.34	0	0	0	0
3	463674	116527	0.02	1.56	0	0	0	0
4	151199	122431	1.10	1.35	0	0	0	0
5	72000	124541	0.87	0.79	0.02322	0.02403	41789	74830
6	18360	108600	1.17	1.06	0.00970	0.01006	4452	27318
7	108001	123286	1.33	1.48	0	0	0	0
8	172802	122955	1.42	1.70	0	0	0	0
9	100802	122963	0.51	0.49	0	0	0	0
10	25920	123883	1.33	1.11	0.00036	0.00042	234	1294
11	161281	113117	1.40	1.54	0	0	0	0
12	43201	123849	1,56	1.48	0	0	0	0
13	69121	121013	1.32	1.15	0	0	0	0
14	24480	124024	1.32	1.02	0	0	0	0
15	53999	121218	1.17	0.92	0	0	0	0
16	144000	116911	1.34	1.48	0	0	0	0

Table 3. Management model 1: Comparison of non-optimized (Sim0) and optimized (GA) pumping strategies. Control variables are discharge (Q), head (h), normalized concentration (c) and salt mass (S).

	Sim0	GA	Δ	%
Total abstraction (m^3/yr)	1830241	1811708	-18533	-0.01
Average head (m)	1.15	1.26	+0.11	+9.2
Total salt mass (kg/yr)	343697	119262	-224434	-65.3

Table 4. Management model 1: Overall performance of non-optimized (Sim0) and optimized (GA) pumping strategies and relative benefits.

4.2 Management model 2 (with recharge)

The second management model is also based on the objective function of equation (1) but in presence of artificial recharge. To this end, 9 artificial recharge scenarios are considered based on 3 different injection locations (1-3, Figure 2) and 3 freshwater recharge volumes (0.5, 1.0 and 1.5 Mm^3/year), respectively. Recharge scenarios are classified with two numbers (e.g. sim13): the first one indicates the injection location and the second one the total freshwater recharge volume. The maximum allowed pumping rate at the well Q_{max} (Table 2) is kept constant for all scenarios. Figure 5 shows the pumping rates at the wells for the 9 optimal scenarios. Table 5 shows values of control variables: h (m), c (/) and S (kg/yr), when the 3 recharging locations are injected with 1.5 Mm^3/yr. The overall performance of the system is summarized in Table 6, showing a salt mass decrease larger than 73%, with reference to current non-optimized condition.

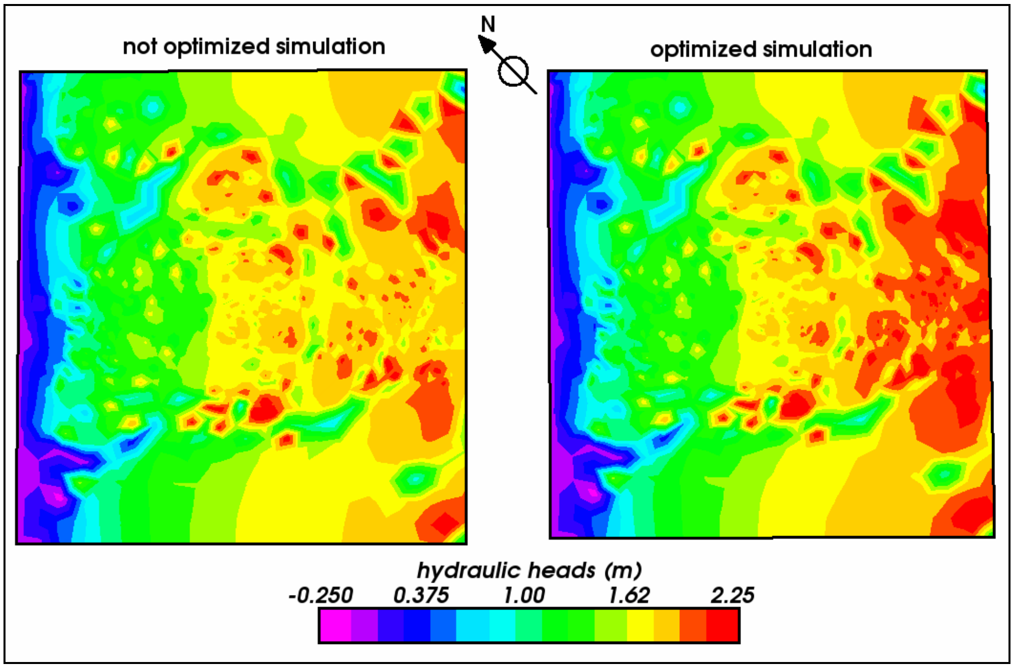

Figure 4. Management model 1: Hydraulic head map at the upper aquifer layer: non-optimized (left) and optimized (right) scenarios.

The 2nd management model has been also performed increasing by 25% the maximum allowed pumping at the well (Q_{max}* = 0.00494 m^3/s) for all the scenarios. Table 7 summarizes overall control values when the three recharging locations are injected with 0.5 Mm^3/yr, compared to non-optimized conditions.

Well id	h (m)			c (/)			S (kg/yr)		
	Sim13	Sim23	Sim33	Sim13	Sim23	Sim33	Sim13	Sim23	Sim33
1	1.65	1.65	1.62	0.09285	0.09285	0.09620	5604	5603	18779
2	1.97	1.65	1.42	0	0	0	0	0	0
3	2.38	1.90	1.63	0	0	0	0	0	0
4	2.16	1.66	1.46	0	0	0	0	0	0
5	0.85	0.85	0.87	0.01990	0.01977	0.01891	58025	57625	49065
6	1.13	1.13	1.15	0.00824	0.00817	0.00763	20794	20622	21788
7	2.25	1.80	1.57	0	0	0	0	0	0
8	2.37	2.03	1.85	0	0	0	0	0	0
9	0.80	0.76	0.61	0	0	0	0	0	0
10	1.22	1.23	1.29	0.00029	0.00028	0.00023	880	853	570
11	1.95	1.96	1.65	0	0	0	0	0	0
12	1.70	1.71	1.57	0	0	0	0	0	0
13	1.50	1.57	1.33	0	0	0	0	0	0
14	1.31	1.39	1.14	0	0	0	0	0	0
15	1.16	1.27	1.04	0	0	0	0	0	0
16	1.88	1.89	1.57	0	0	0	0	0	0

Table 5. Management model 2: Control variables at the wells for the injection scenarios with a total recharge of 1.5 Mm^3/yr.

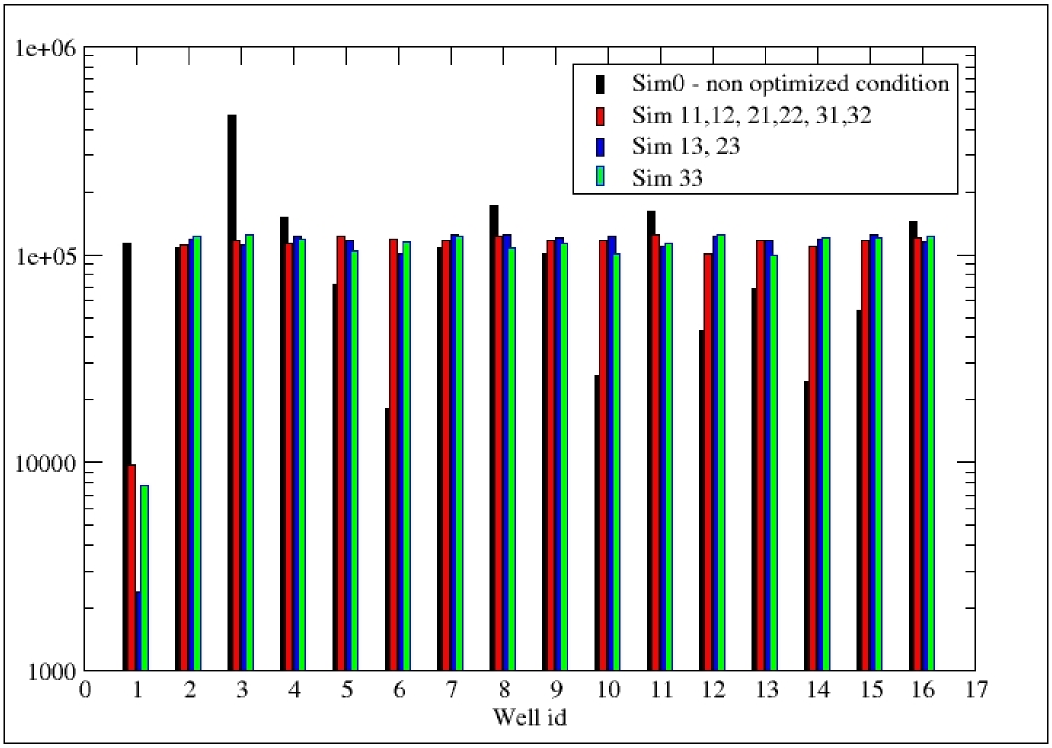

Figure 5. Management model 2: Optimal pumping rates for the 9 recharge scenarios.

	h (m)	Δh	%	S (kg/yr)	ΔS	%
Sim0	1.15	-	-	343697	-	-
Sim13	1.64	+0.49	+42.8	85302	-258395	-75.2
Sim23	1.53	+0.38	+33.0	84703	-258993	-75.4
Sim33	1.36	+0.21	+18.3	90203	-253494	-73.8

Table 6. Management model 2: Overall performance of non-optimized (sim0) and optimized pumping strategies with a total recharge of 1.5 Mm^3/yr, and the relative benefits.

	h (m)	Δh	%	S (kg/yr)	ΔS	%
Sim0	1.15	-	-	343697	-	-
Sim11*	1.23	+0.08	+6.6	149516	-149180	-56.5
Sim21*	1.19	+0.04	+3.3	149189	-149508	-56.6
Sim31*	1.14	-0.02	-1.9	146885	-196812	-57.3

Table 7. Management model 2: Overall performance of non-optimized (sim0) and optimized pumping strategies with a total recharge of 0.5 Mm^3/yr and an increase of 25% in maximum pumping at the well.

5 CONCLUSIONS

Two aquifer management models (with and without artificial recharge) have been considered for the inner region of the coastal aquifer within a 1 year time interval. Results of the no-injection optimization model identified the optimum spatial distribution of pumping rates at the 16 control wells, showing an average increase of 0.10 m in water table levels and a marked decrease of 65% in the total extracted salt mass, while keeping the 99% of total abstraction, with reference to current non-optimized conditions. Results of the mixed injection-pumping optimization model identified optimum recharge locations among 9 configurations and the spatial distribution of pumping rates at the wells, allowing to withdrawal the 95% of the total current pumping rate, while lowering the total extracted salt mass up to 25% and recovering water table levels in a range of +0.15-0.40 m, with reference to current non-optimized conditions. Further development is foreseen to extend these encouraging results to the whole aquifer system, including into the analysis economic costs and parameter uncertainty.

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