Reservoir-aquifer combined optimization for groundwater restoration: The case of Lake Karla watershed, Greece

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Reservoir-aquifer combined optimization for groundwater restoration: The case of Lake Karla watershed, Greece

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Abstract: The implementation of environmental projects, which has been very successful when restoring degraded water resources, is by itself not enough. The optimum combined operation of artificial water resources and natural systems, plays a crucial role in achieving sustainable management. This study presents a methodology for the simulation and optimization of Lake Karla watershed groundwater use for domestic water supply and irrigation, under two constraints of groundwater restoration. This is achieved by using a coupled modeling system of artificial and natural water resources simulation and a conjunctive groundwater optimization-simulation model. The groundwater flow model simulates the operation of the alluvial phreatic aquifer under different groundwater management scenarios. The management model GWM estimates the optimum pumping rates, the number and the locations of irrigation and domestic water supply wells. Optimal pumping rates were inserted into the groundwater flow model and the hydraulic head maps of the aquifer and the volumetric budget was estimated. Four alternative management scenarios for the location of 40 water supply wells for the city of Volos have been studied and optimized. These water supply wells are part of the Lake Karla restoration project and they will be located at the southern part of the aquifer, where the greatest drawdown of the water table has been observed. The management scenarios were evaluated regarding the two environmental constraints of groundwater rehabilitation and the optimal groundwater use.

Key words: Modelling system, combined optimization, aquifer restoration, optimal groundwater exploitation

1. INTRODUCTION

The increasing demand of water to cover the needs of raising production and the climate change impact makes today the optimal use of water imperative, especially in semi arid regions like Greece. Furthermore, the lack of sustainable water resources management has led to environmental degradation especially on groundwater resources (Qin et al., 2011). One way to overcome this problem is the construction of environmental projects. Engineers have succeeded in the construction and the application of even huge environmental projects to protect water exploitation and to restore environmental problems (WWAP, 2012). To achieve this, a sustainable water resource management plan is mandatory. Successful tools for this plan orientation are the simulation and optimization models for both water resources and environmental projects. This technique has been successfully applied for the evaluation of alternative engineering scenarios and the selection of the optimal schemes (Gorelick, 1983; Ahfeld and Heidari, 1994; Sinhg, 2012). Simulation models provide solutions that obey the equations governing the relevant processes in the system and check for feasibility of a management strategy, while optimization models identify an optimal management strategy from a set of feasible alternative strategies (Das and Datta, 2001). This is done in this study, as a series of simulation, reservoir's operation and optimization models are linked and applied successfully for the optimal exploitation of Lake Karla watershed renewable groundwater, in order to cover the water supply and irrigation needs and to restore aquifer's water table at a satisfactory level in future time.

2. STUDY AREA

Lake Karla watershed covers an area of 1171 km^2 and is located in the eastern part of Thessaly region of central Greece (Figure 1). It lies between latitude 39°20′56′′ to 39°45′15′′ N and longitude 22°26′10′′ to 23°0′27′′ E. The climate is typical Mediterranean. Summers are usually very hot and dry, and in July and August temperatures may reach up to 40°C. The average temperature is 16 °C – 17 °C. The mean annual precipitation varies from about 500 mm to 700 mm (Sidiropoulos et al., 2012). Dense forests with traditional villages occupy the mountainous area, while the plain is the most productive agricultural area in Greece, without the presence of urban and industrial areas. The database of CORINE Land Cover 2000 for Greece [EEA, 2007] was used in order to identify land use types of the catchment area. The major crops are cotton, wheat, alfa-alfa, corn, tobacco and orchards (Vasiliades et al., 2009). Schist and karstic limestones or marbles prevail in the mountains. The plain, where the aquifer is located, consists mainly of recent grains of various sizes originating from Lake Karla deposits.

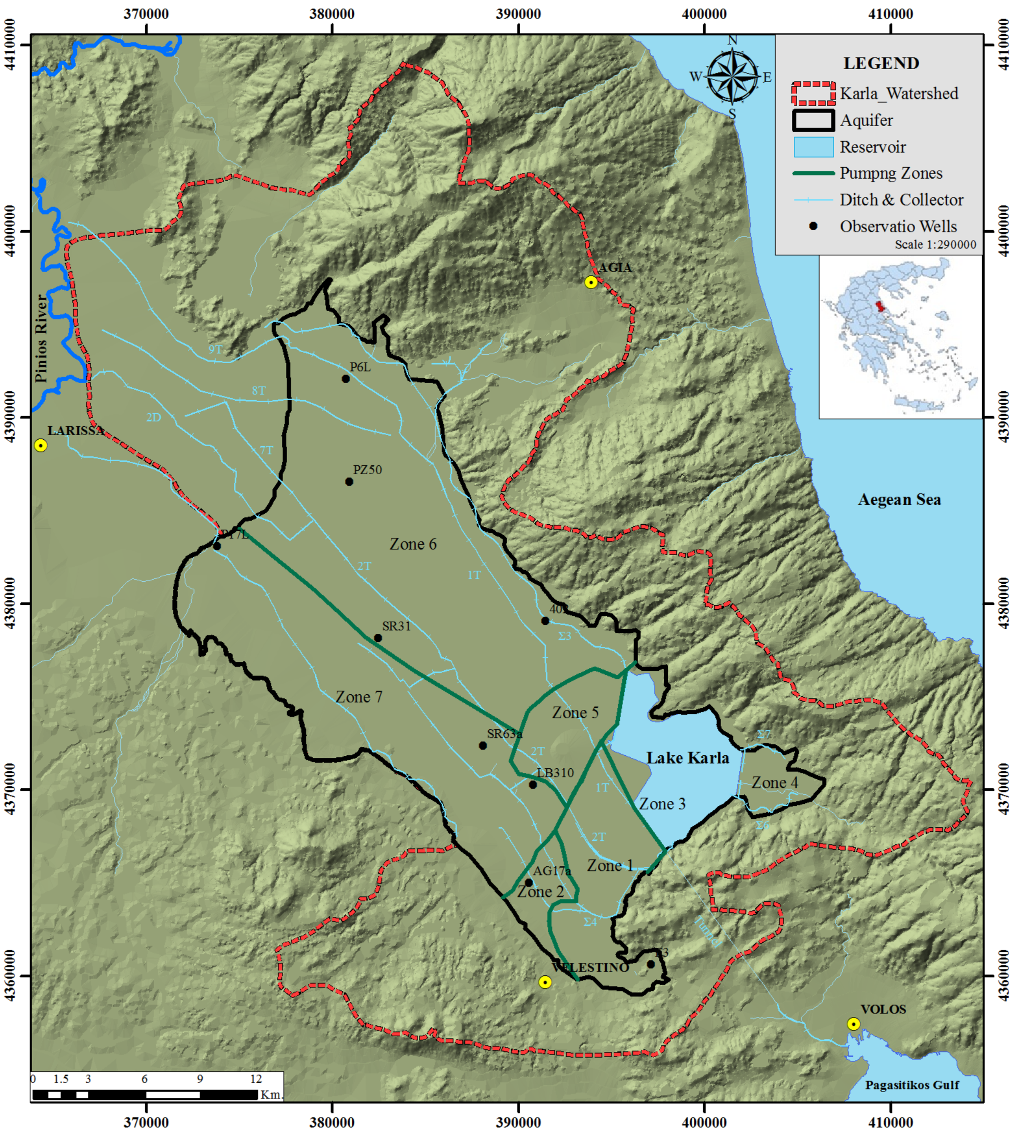


Figure 1. Map of Lake Karla basin, indicating the aquifer, reservoir of Lake Karla, the irrigation zones and the observation wells.

The aquifer of Lake Karla watershed is a characteristic paradigm of groundwater degradation, due mainly to three factors:

1. The Lake Karla's drainage in 1962.

2. The long-standing cultivation of water demanding crops in Karla's plain and the unsustainable pumping of groundwater to cover the irrigation water demands.
3. The lack of strategy and policies for sustainable water resources management and the lack of irrigation systems. Actually, an old irrigation system consisting of non-maintained earth canals partially cover the irrigation needs of the crops which are located at the north south part of Lake Karla watershed.

The aquifer's hydraulic head showed a significant drop the last decades as it is presented in the graph of Figure 2.

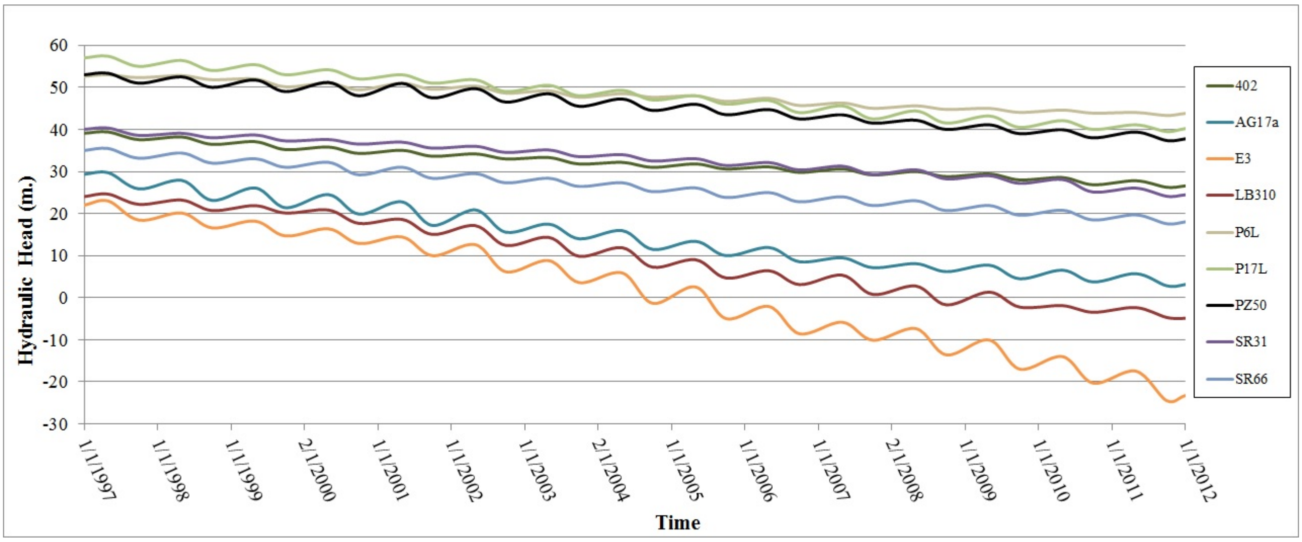


Figure 2. Hydraulic head time series plots for ten observation wells (period 1997-2012)

Former Lake Karla occupied the lowest part of its natural basin and was considered as one of the most important wetlands in Greece until 1962. It was the only surface water body of the watershed. Surface runoff from the watershed and floodwaters of the Pinios River (discharging via the Asmaki ditch – 8T) supplied the lake with large quantities of freshwater. Its surface area fluctuated between 40 km^2 and 180 km^2. In 1962, complete drying of the lake took place in order to create more land for agriculture and to avoid the flooding of the low elevation lands because of its surface area fluctuations. But, this has created many environmental and ecological problems with anthropogenic impacts including wetland loss, significant drawdown of the aquifer's water table, subsequent soil salinization and loss of ecological and aesthetic value (Zalidis et al., 2004).

The reconstruction of Lake Karla targets to inverse this problem. The reconstructed Lake Karla occupies the lowest part of the former Lake Karla. It lies between latitude 39°26΄49΄΄ to 39°32΄03΄΄ N and longitude 22°46΄47΄΄ to 23°51΄50΄ E and has a surface of 38 km^2 (Figure 1). It is characterized by its shallow depth with a maximum water depth of 4.5 m and a mean depth of 2 m. Two systems of ditches (2D-7T-2T and 8T&9T-1T) transfer the flood runoff of Pinios river to the reservoir, as happened in the past with the former Lake Karla, as it is located in the lower part of Karla basin. Furthermore, four collector channels (Σ3, Σ4, Σ6, Σ7) collect the surface runoff from the higher elevation zones of the watershed and directly divert it into the reservoir. The surface runoff of the lower elevation areas is pumped into the reservoir. So, the maximum allowable volume of reservoir reaches up the 180 hm^3, but only the 46 hm^3 is available to cover the irrigation needs of the surrounding agricultures because of the environmental restraints, as the water level of the reservoir will have to be always higher than the absolute height of +46.40 m satisfying ecological criteria as a wetland.

3. METHODOLOGY

In this study, a coupled modeling system has been applied consisting of a surface water simulation model, a reservoir operation model and a reservoir/lake-aquifer interaction model and a simulation-optimization model of groundwater flow and management. These models are: the UTHBAL (Loukas et al., 2007) for the assessment of the surface hydrology, the UTHRL (Loukas et al., 2007) for reservoir operation simulation, the LAK3 (Merritt and Konikow, 2000) for reservoir/lake-aquifer interation simulation, the USGS MODFLOW (Harbaugh and McDonald, 2000) for groundwater flow simulation and the USGS GWM (Ahlfeld et al., 2005) for groundwater management and optimization. This modeling system has been developed under the research project "HYDROMENTOR". The models have been presented in a recent paper (Sidiropoulos et al., 2013). The models are linked and coupled sequentially to each other according to the following procedure: the UTHBAL model calculates the basin surface runoff and the groundwater recharge and passes the first variable to UTHRL and the second variable to MODFLOW, respectively. Then, the UTHRL model balances the inflows and outflows of the reservoir and passes the inflows, evaporation and water withdrawals of the reservoir to LAK3 model. The LAK3 model calculates the reservoir seepage to groundwater and passes this variable to the MODFLOW model. MODFLOW uses the inflows of recharge, reservoir leakage and the withdrawals from wells to calculate the groundwater flow and create maps of the hydraulic heads and estimate the volumetric budget of the aquifer. Finally, GWM uses the MODFLOW results and solves the optimization problem. The optimum extracted groundwater volumes of wells from GWM are imported to the MODFLOW model to estimate the aquifer response.

According to the Lake Karla recostruction project, forty water supply wells will gradually be established in a zone close to the reservoir (Sidiropoulos et al., 2015) (zone 1) for covering the domestic needs of 15.7 hm^3/y for Volos city (Mpezes, 2004). This zone is located in the most degraded area of the aquifer where the largest water table drawdown has been observed (Sidiropoulos, 2014). The water supply project of Volos by pumping groundwater from Lake Karla aquifer aims to provide a low cost solution. The southern part of the aquifer has been selected because this area is close to the city of Volos, the length of pipelines needed is small and no construction of any additional pumping station is required. This is the reason for selecting the southern part of the aquifer. Additionally, this paper examines the environmental sustainability of groundwater resources using an optimization process and no reference is made to economic issues. Sidiropoulos et al. (2009) have proven that the operation of these wells will reverse the positive contribution of reservoir operation in the restoration of groundwater.

A series of papers have been published by the authors on the modelling and management of groundwater of Lake Karla aquifer under present and future climate change scenarios and for various water resources management scenarios and strategies (i.e. Sidiropoulos et al., 2009; Sidiropoulos et al., 2013; Mylopoulos and Sidiropoulos, 2014; Sidiropoulos et al., 2015). This study uses the same modelling system and the knowledge gained from the previous studies. However, the present paper is the first one that investigates alternative management scenarios for optimum location of pumping wells and their extraction rates leading to aquifer rehabilitation. In total, four (4) alternative management scenarios have been simulated for the optimization of the location of Volos water supply wells and their pumping rates.

The groundwater flow model simulates the operation of the alluvial phreatic aquifer for both the historical period from 1987 to 2012 and for the 2012-2044 future management period, as the reservoir was planned to be in operation in 2012. The major water uses of the watershed are the agricultural and the urban (Loukas et al., 2007). The water demands were calculated according to a method presented in the paper of Mylopoulos and Sidiropoulos (2014) by dividing the area of the aquifer to seven pumping zones (Figure 1; Table 1). The future irrigation needs were assumed to be the historical ones. For the precipitation and temperature data, one timeseries covering the whole period 1987-2044 was generated. Specifically, for the period 2012-2044, a synthetic monthly

precipitation and temperature data series, based on a Thomas-Fiering model (Thomas and Fiering, 1962), has been generated.

Table 1. The mean annual groundwater extraction (in hm^3) for the seven pumping zones of the study area (as indicated in Figure 1) for the historical period 1987-2012.

Pumping Zones (as indicated in Figure 1)		1	2	3	4	5	6	7
Mean Annual extracted groundwater volume for the period 1987-2012 (hm^3)	Irrigation	22.0	3.6	5.9	3.3	2.2	38.5	55.7
	Water supply	2.4	0	0	0.2	0.3	0	0
	Sum	**24.4**	**3.6**	**5.9**	**3.5**	**2.5**	**38.5**	**55.7**

The management model GWM estimates the optimum pumping rates and locations of the boreholes by solving an optimization problem for the sustainable groundwater management. The optimum pumping rates are inserted into the MODFLOW model which calculates the hydraulic head maps of the aquifer and its volumetric budget. The year 2044 is a "milestone", set by the project designers for the reconstitution of Lake Karla, for the restoration of groundwater.

Four alternative management scenarios for the installation of forty water supply wells for the Volos city have been studied and optimized. These new water supply wells are part of the Lake Karla restoration project and they will be located, according to the plan, at the southern part of aquifer, where the greatest drawdown of the water table is observed. The four management scenarios have been applied to substantiate the effect of the water supply wells operation on the optimum extraction of groundwater for two different constraints for the year 2044: i) a water table level corresponding to that of 1987, which was the last year of aquifer’s positive volumetric budget (First constraint) and ii) a water table level equal to the sea water level (i.e. absolute elevation 0 m) (Second constraint). Only the irrigation wells of zones 6 and 7 participated in the optimization problem, as reservoir covers the irrigation needs of zones 1, 2, 4 and 5 (Fig. 1).

The optimization/management problem is formulated as follows:

$$Maximize \sum_{t=1}^{T} \sum_{n=1}^{N} Q_n^t \quad (1)$$

subject to the following constraints:

i) First constraint

$$h_i^{2044} \geq h_i^{1987}, i = 1,........, m \quad (2)$$

or

ii) Second constraint

$$h_i^{2044} \geq 0m, i = 1,........, m \quad (3)$$

$$Q_n \geq 0m^3/s, n = 1,......N \quad (4)$$

where Q_n is the groundwater withdrawal flow rate of the managed wells in m^3/d, N is the total number of managed wells, T is the number of monthly stress periods for the management period 2012-2044, h_i is the hydraulic head constraint where the exponent refers to the year and m is the number of head constraints points. The non linearity form of the objective function is solved by sequential linear programming algorithm (SLP), which has been used before in relevant case studies (Ahlfeld and Baro-Mentes, 2008; Banta and Paschke, 2012; Singh et al., 2013). It is based on repeated linearization of the non-linear features of the management problem and is implemented by

recalculating the response matrix for each sequential linear programming. The target of the optimization problem is to find the maximum allowable extraction volume of groundwater for the period 2012-2044, in order the hydraulic heads of the wells at the end of the management period to be equal or higher than the ones of year 1987 or than of 0 m. Figure 3 presents a map of the hydraulic head distribution in the aquifer for 01/1987. Although the coverage of domestic water supply is the criterion of management scenarios comparison, no priority has been given to water supply wells in the optimization problem.

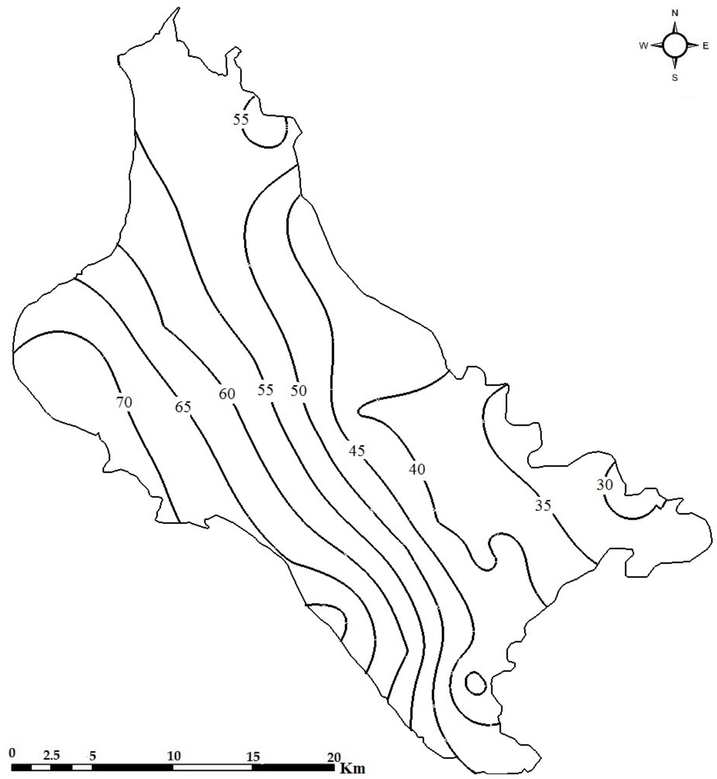


Figure 3. Hydraulic head (m) distribution in Lake Karla aquifer for 01/1987.

The four management scenarios deal with the installation and operation of the new water supply wells in zones 1, 2, 4, 5 respectively. Zone 3 has not been selected as it covers the location of the reservoir. Zones 6 and 7 have not been selected, as they are not covered by the new Lake Karla irrigation system and they will not be supplied with water from the reservoir. Finally, the optimized wells are the irrigation wells of zones 6 and 7 and the forty new supply wells.

4. RESULTS

Table 2 shows the number of optimized wells with the annual extracted groundwater volume per zone and per use (i.e. irrigation or water supply) for the first constraint. In the same table (Table 2) the mean annual renewable groundwater volume and the volumetric budget of the aquifer are presented for each scenario. The optimization problem has no solution for the scenarios 1 and 2 (i.e. location of the water supply wells in zones 1 and 2, respectively). The reason is that water table drawdown is so large that the constraint cannot be achieved.

The renewable groundwater volume is the sum of the natural recharge, lateral inflow, irrigation return flow and reservoir seepage. A large percentage of the renewable groundwater volume (i.e. 19.78 hm^3/y) is committed for the water table restoration. Once this target is achieved, the criterion for the scenario evaluation is the water volume used for the domestic water supply of Volos city. Scenario 4 resulted in larger water supply volume than scenario 3. However, the two feasible

scenarios could not satisfy the total domestic water supply annual volume which amounts to 15.7 hm^3.

Table 2. Results of the optimization problem for the first constraint

Scenario 3 - 40 supply wells in zone 4									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		0	0	0	10	0	34	52	96
Annual Extracted	Irrigation	0	0	0	0	0	13.47	21.45	34.92
Volume (hm^3)	Water Supply	0	0	0	2.74	0	0	0	2.74
Total Annual Extracted Volume (hm^3)									**37.66**
Mean annual renewable (hm^3)									**57.44**
Scenario 4 - 40 supply wells in zone 5									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		0	0	0	0	28	31	45	104
Annual Extracted	Irrigation	0	0	0	0	0	12.47	16.61	29.08
Volume (hm^3)	Water Supply	0	0	0	0	8.58	0	0	8.58
Total Annual Extracted Volume (hm^3)									**37.66**
Mean annual renewable (hm^3)									**57.44**

Table 3 presents the optimization results for the second constraint and the four management scenarios.

Table 3. Results of the optimization problem for the second constraint

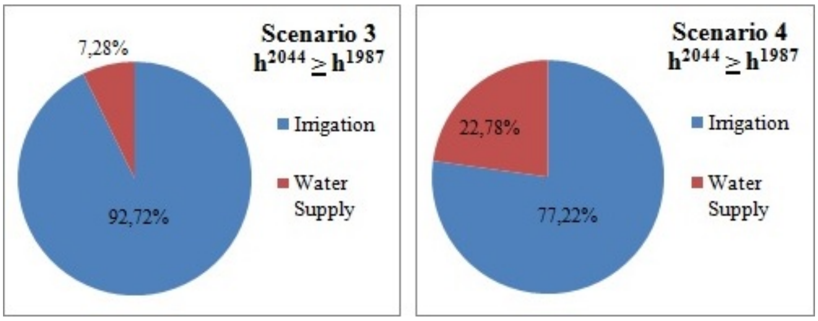
Scenario 1 - 40 supply wells in zone 1									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		32	0	0	0	0	44	52	128
Annual Extracted	Irrigation	0	0	0	0	0	17.26	20.92	38.18
Volume (hm^3)	Water Supply	9.49	0	0	0	0	0	0	9.49
Total Annual Extracted Volume (hm^3)									**47.67**
Mean annual renewable (hm^3)									**57.44**
Scenario 2 - 40 supply wells in zone 2									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		0	36	0	0	0	42	49	127
Annual Extracted	Irrigation	0	0	0	0	0	16.84	19.92	36.76
Volume (hm^3)	Water Supply	0	10.91	0	0	0	0	0	10.91
Total Annual Extracted Volume (hm^3)									**47.67**
Mean annual renewable (hm^3)									**57.44**
Scenario 3 - 40 supply wells in zone 4									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		0	0	0	36	0	42	49	127
Annual Extracted	Irrigation	0	0	0	0	0	15.97	19.92	35.89
Volume (hm^3)	Water Supply	0	0	0	11.78	0	0	0	11.78
Total Annual Extracted Volume (hm^3)									**47.67**
Mean annual renewable (hm^3)									**57.44**
Scenario 4 - 40 supply wells in zone 5									
Zones		1	2	3	4	5	6	7	Sum
Number of optimized wells		0	0	0	0	40	41	45	126
Annual Extracted	Irrigation	0	0	0	0	0	15.63	18.62	34.25
Volume (hm^3)	Water Supply	0	0	0	0	13.42	0	0	13.42
Total Annual Extracted Volume (hm^3)									**47.67**
Mean annual renewable (hm^3)									**57.44**

In all of four scenarios and under the second constraint, the annual volume of renewable groundwater committed for water table rehabilitation is 9.77 hm^3. The simulation – optimization process resulted in mean annual renewable water volume (i.e. natural recharge, lateral inflow, irrigation return flow and reservoir seepage) equal to 57.44 hm^3 and mean annual extracted water volume equal to 47.67 hm^3. Additionally, the results of the groundwater modelling have shown that there is no groundwater outflow to the adjacent western aquifer, because the Lake Karla's aquifer water table is lower than the water table of the adjacent aquifer. As a result, the groundwater volume available for aquifer rehabilitation is the difference between the mean annual renewable

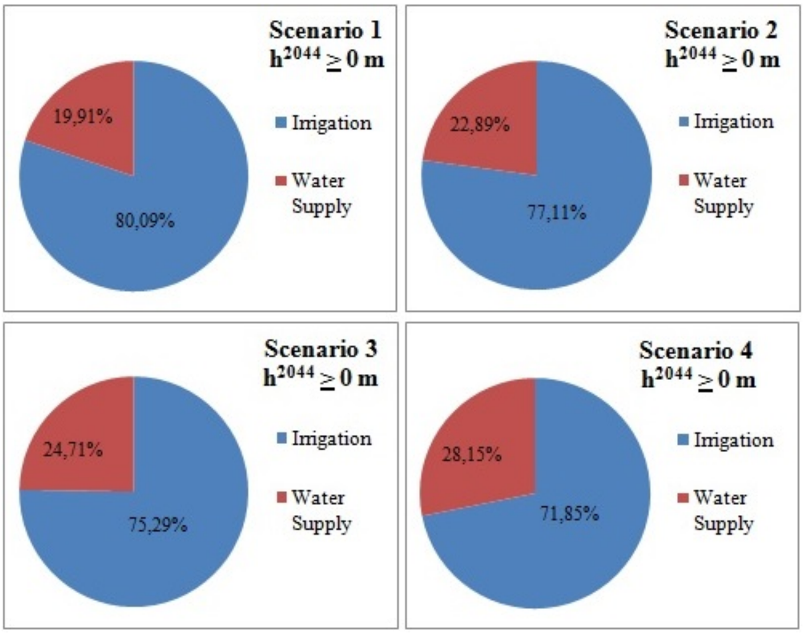
water volume (57.44 hm^3) and the mean annual extracted water volume (47.67 hm^3). As a result, larger volume of groundwater extraction was used for water supply of Volos city than the respective volume found under the first constraint.

It is clear from the optimization results that the groundwater zones 4 and 5 are able to provide more water for domestic water supply because the aquifer is less degraded than in the other zones. Furthermore, the zones 4 and 5 are in the vicinity of the reservoir and the aquifer is positively affected by reservoir seepage. The most appropriate zone for the establishment and operation of the water supply wells is zone 5 for both constraints. However, the four feasible scenarios for the second constraint could not satisfy the total domestic water supply annual volume which amounts to 15.7 hm^3, even for the optimum solution (i.e. scenario 4-water supply wells in zone 5).

The results for all scenarios and the two constraints indicate that the reconstruction and operation of the Lake Karla reservoir could not successfully restore the aquifer when water is pumped for domestic water supply. This finding confirms the results of a previous paper (Sidiropoulos et al., 2009).



a.



b.

Figure 4. a, b. Percentages of the optimum extracted groundwater volume for irrigation and domestic water supply.

Figure 4 presents the percentages of the optimum extracted groundwater volume for irrigation and domestic water supply for the feasible scenarios and the two constraints. These results indicate that the optimum groundwater volume used for domestic water supply increases in expense of the optimum extracted groundwater volume used for irrigation because a certain volume of

groundwater is committed for aquifer water table rehabilitation. The annual domestic water supply demands (15.7 hm^3) could be covered if priority is put to water supply use by increasing the weighing of water supply in the objective function (Equation 1). However, this optimization scheme will lead to very small coverage of the irrigation needs.

5. CONCLUSIONS

In this study, a coupled modeling system has been used for the optimization of conjunctive groundwater use for irrigation and water supply under two environmental constraints for groundwater restoration. The two environmental constraints were: i) a water table level corresponding to that of 1987, which was the last year of aquifer's positive volumetric budget (First constraint) and ii) a water table level equal to the sea water level (i.e. absolute elevation 0 m) (Second constraint).The model has been applied to Lake Karla aquifer. Four (4) alternative management scenarios regarding the location of the water supply wells have been examined. As a result, the feasible management scenarios for the two environmental constraints have been simulated and the optimum location and number of wells and their groundwater pumping volumes have been estimated.

The results indicate that:

1. None of the two constraints can be satisfied if the total water supply demands are extracted (i.e. 15.7 hm^3),
2. The first constraint cannot be satisfied if the domestic water supply wells are located and operate in zones 1 and 2. Zone 1 is the location where the forty water supply wells will be installed according to the Lake Karla restoration project,
3. A total annual water volume of 19.78 hm^3 of the renewable groundwater is committed for groundwater restoration under the first constraint,
4. A total annual water volume of 9.77 hm^3 of the renewable groundwater is used for groundwater rehabilitation under the second constraint,
5. The required volume for groundwater restoration for the two constraints (i.e. points 3 and 4) result in increased optimum water supply volume in expense of the optimum extracted groundwater volume used for irrigation.

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REFERENCES

Ahlfeld, D.P., Barlow, P.M., Mulligan, A.E., 2005. *GWM—A ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000)*. U.S. Geological Survey Open-File Report 2005-1072, Denver.

Ahlfeld, D.P., Heidari, M., 1994. Applications of optimal hydraulic control to groundwater systems. Journal of Water Resources and Planning Management, ASCE; 120(3):350–365.

Ahlfeld, P., Baro-Mentes, G., 2008. Solving unconfined groundwaterflow management problems with successive linear programming. Journal of Water Resources Planning and Management, ASCE; 134(5):404-412.

Banta, E.R., Paschke, S.S., 2012. *Demonstration optimization analyses of pumping from selected Arapahoe aquifer municipal wells in the west-central Denver Basin, Colorado, 2010–2109*. U.S. Geological Survey Scientific Investigations Report 2012 – 5140, 37p.

Das, A., Datta, B., 2001. Application of optimisation techniques in groundwater quantity and quality management. Journal of Sadhana; 26(4):293-316.

E.E.A., 2007. European Environmental Agency data service. http://dataservice.eea.europa.eu/dataservice/ (accessed 08.09.07)

Gorelick, S.M., 1983. A review of distributed parameter groundwater management modeling methods. Journal of Water Resources Research; 19(2):305–319.

Harbaugh, A.L., McDonald, M.G., 2000. *User's Documentation for MODFLOW-2000, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model*. United States Government Printing Office, Washington.

Loukas, A., Mylopoulos, N., Vasiliades, L., 2007. A Modelling System for the Evaluation of Water Resources Management Scenarios in Thessaly, Greece. Water Resources Management; 21:1673 – 1702.

Merritt, M.L., Konikow, L.F., 2000. *Documentation of a Computer Program to Simulate Lake-Aquifer Interaction Using the MODFLOW Ground-Water Flow Model and the MOC3D Solute-Transport Model***.** U.S. Geological Survey, Water-Resources Investigations Report 00-4167, USA.

Mpezes, K., 2004. *Study for the aim of supply water projects of the greater area of Volos*. Greek Ministry of Environment, Regional Planning and Public Works, Athens.

Mylopoulos, M., Sidiropoulos, P., 2014. A stochastic optimization framework for the restoration of an over-exploited aquifer. Hydrological Sciences Journal (Online). doi: 10.1080/02626667.2014.993646.

Qin, D., Qian, Y., Han, L., Wang, Z. Li. C., Zhao, Z. 2011. Assessing impact of irrigation water on groundwater recharge and quality in arid environment using CFCs, tritium and stable isotopes, in the Zhangye Basin, Northwest China. Journal of Hydrology; 405:194–208.

Sidiropoulos, P., 2014. *Groundwater resources management undr cinditions of uncertainty: The value of information in environmentally degraded aquifers*, Doctoral Thesis, University of Thessaly, Volos, Greece (in Greek).

Sidiropoulos, P., Mylopoulos, N., Loukas, A., 2009. Simulation of the new water supply wells' influence on Karla's aquifer. *Common Congress: 11^{o} of Hellenic Hydrotechnical Association (HEA), 7^{o} of Greek Cimmittee for Water Resources Management (GCWRM) «Integrated Water Resources managenent under climate change conditions»*, Volos, Greece.

Sidiropoulos, P., Mylopoulos, N., Loukas, A., 2013. Optimal management of an overexploited aquifer under climate change: The Lake Karla case, Journal of Water Resources Management; 27(6):1635-1649.

Sidiropoulos, P., Mylopoulos, N., Loukas, A., 2015. Stochastic Simulation and Management of an Over-Exploited Aquifer Using an Integrated Modeling System, Journal of Water Resources Management; 29(3):929-943.

Sidiropoulos, P., Papadimitriou, Th., Stabouli, Z., Loukas, A., Mylopoulos, N., Kagalou, If., 2012. Past, present and future concepts for conservation of the re-constructed lake Karla (Thessaly- Greece), Fresenius Environmental Bulletin; 21:10a.2012.

Singh, A., 2012. An overview of the optimization modeling applications. Journal of Hydrology; (466-467):167-182.

Singh, A., Burger, M.C., Cirpka A.O., 2013.Optimized Sustainable Groundwater Extraction Management: General Approach and Application to the City of Lucknow, India.Journal of Water Resources Management; 27(12):4349-4368.

Thomas, H.A., Fiering, M.B., 1962. *Mathematical synthesis of streamflow sequences for the analysis of river basins by simulation. In: Design of Water Resources Systems*, (Ed. by A. Maas *et al.)* Chapter 12. Harvard University Press, Cambridge, Mass.

Vasiliades, L., Loukas, A., and Patsonas, G., 2009. Evaluation of a statistical downscaling procedure for the estimation of climate change impacts on droughts. Nat. Hazards Earth Syst. Sci.; 9:879-894.

Wagner, J.W., 1995. *Recent advances in simulation-optimization groundwater management modeling. U.S. National Report to International Union of Geodesy and Geophysics 1991-1994*, Reviews of Geophysics, Supplement, 1021-1028

WWAP (World Water Assessment Programme). 2012. *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*. Paris, UNESCO.

Zalidis, G.C., Takavakoglou, V., Panoras A., Bilas, G., Katsavouni, S., 2004. Re-establishing a sustainable wetland at former Lake Karla, Greece, using Ramsar restoration guidelines. Journal of Environmental Management; 34(6):875-886.