An integrated approach for sustainable water resources management of Messara basin, Crete, Greece

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Abstract: A methodology for an integrated water resources management was developed for a typical Mediterranean island environment with limited field data. The Penman-Monteith method was found the most appropriate to evaluate the potential evapotranspiration. The Sacramento model was used to calculate the hydrologic equilibrium of the basin and to provide the spatiotemporal distribution of the infiltration as an input to the Modflow model, along with a detailed hydrogeological structure of the basin in order to simulate the groundwater budget. The water resources management program RIBASIM was used to provide the results from alternative scenarios. This methodology was successfully applied to the Messara basin in Crete in which an overexploitation of groundwater has occurred in a large number of wells since 1984 and that continues to increase at alarming proportions. A number of alternative measures are suggested for protection and sustainable development of water resources of the Messara area in compliance with the Water European Directive.

Keywords: Integrated water resources management, surface and groundwater modelling, water scarcity, Messara basin, Crete

1. INTRODUCTION

The rapid development of Crete during the last 30 years has exerted strong pressures on many sectors of the region. The growth of agriculture in the Messara plain had a strong impact on the water resources of the area by substantially increasing water demand. The economy of the region is based on agriculture with intensive cultivation; mainly olive trees, grapes, citrus, fruit and vegetables in green houses (CORINE, 2000). The advantage of climatic conditions for the growth of agriculture became a disadvantage to the aquatic environment since plants require certain amounts of irrigated water for an optimum yield production (Chartzoulakis et al, 2001). The total consumptive water for irrigation and domestic use is supplied from groundwater without any planning and consequently is driven to escalate at alarming proportions of the aquifer system (Papagrigoriou et al 2003; Croke et al 2000; Paritsis 2000).

Despite the excellent primary research by the FAO program carried out during the period 1969-1972 (FAO 1970; FAO 1972), which was limited to the area of alluvial aquifer, no further research has taken place, but only some investigation restricted to parts of the basin focused on the construction of new wells.

Water conflicts that have appeared in the basin have motivated the investigations reported in this paper. Additional methods, models and procedures for a realistic approach of water conditions on the scale of a typical Mediterranean water basin have been evaluated. Following the introduction is the methodology, the case study, the data analysis, the surface and ground water modelling, and the integrated water resources management.

2. METHODOLOGY

The methodology to approach the water conditions of the Messara was driven both by limited data and by the individual climatic conditions which are characteristic of the south-eastern

Mediterranean island environment such as the Mediterranean climate, small catchments, ephemeral streams, and special topographical and hydrogeological conditions. The methodology includes the following steps:

- Data analysis of meteorological, hydrological, piezometric (ground water), pumping rates of wells, and water uses; Spatial integration of point data using appropriate methodologies in the GIS environment.
- Hydrological and Hydrogeological setting; simulation of rain-runoff and ground water relied on conceptual model approach along with a detailed hydrogeologic structure of the basin.
- Water supply- demand system; scenarios for sustainable full development of water resources; evaluation of alternative proposals / scenarios for the protection of water resources and furthermore for a sustainable development of the local economy.

3. CASE STUDY

The Messara basin encompasses an area of 611 Km^2 located in the central- southern area of Crete and extends in two catchments: the Geropotamos-Festos and the Anapodaris-Xarakas (Fig. 1). The geomorphological relief is typical of a graben formation and the surface drops within 15 Km from 2,454 m asl in Psiloritis Mountain to 45 m asl at Festos. The Geropotamos River with a westward direction and the Anapodaris River with an eastward direction drain the homonymous catchments. The plain area of the two catchments hosts the largest alluvium aquifer system of the island, which is the only water resource of the broader area nowadays, where a drop in the water table up to 45 m was observed due to overexploitation in a number of wells registered at 845 in the year 2004 and estimated at 1,400 in the year 2007 (YEB 2005; RoC 2005).



Figure 1. Study area – Messara valley

3.1 Hydrological setting

In the study area the quaternary sediments fill the plain of Messara (45 % of the basin) and the surrounded hilly and mountain area (53 %) is filled with neogene sediments and flysch, which are both characterized by a relatively high runoff, while only a small portion (2%) are occupied by karstic formations located on the mountain area, which are characterized by a negligible runoff (Fig. 2). Therefore a rich network system is formed within the basin, which transfers the rain water into the sea within hours or a few days.

The Geropotamos basin has an area of 400.4 km² with mean elevation 307.8 m asl and mean slope 7%. The Anapodaris-Xarakas basin has an area of 210.6 km² with mean elevation 361.8 m asl and mean slope 6.7%. The existing monitoring system comprises three hydrometric stations named: Festos, Lithaios and Plakiotissa, the daily flow data of which has been published since 1973 (Fig. 2).



Figure 2. Simplified hydrogeological map of Messara basin. In general, alluvium and conglomerates outcrops at the central part of the study area showing medium permeability, Neogene sediments (mainly marls with intercalations of marly limestones, sandstones and gypsums) outcrops at the north part with low to very low permeability, and the south massifs consist mainly of flysch and gneiss and a small outcrop of carbonate rocks (karstified limestones)(modified after geological maps of IGME)

3.2 Hydro-Geological setting

The geology of Crete can be described in terms of a pile of four pre-Neogene major nappes and one autochthonous isotopic zone with a cumulative thickness of 6.5 km. The nappes were transported from the north along E-W trending thrusts and were placed between Late Eocene and Early Miocene times. Shortly after nappe emplacement during the Middle/late Miocene an N-S directed extensional regime was established in the region, due to the relative plate behavior and the

resultant geodynamic condition at the European margin, where the first E-W trending basins were formed. Followed by two main faults generation: a) in the late Messinian an arc- parallel extension formed the N-S trending and smaller basins and b) in middle Pliocene a fault development resumed in two normal directions NW-SE and NE-SW (Fassoulas 2001a,b). This period was associated with the deposition within the graben of Miocene to Quaternary sediments, which consist mainly of red beds, sandstones, marls, limestones and evaporites. On top of them red lacustrine conglomerates and recent alluvium sediments have been deposited

The Messara basin has an asymmetrical elongate shape oriented in an E-W long axis bounded by normal faults. Within the basin the above mentioned three main fault generations are recognized. The plain area of the Messara consists of alluvial-Pleistocene fills, the hilly region composed of Neogene rocks with locally protruding Mesozoic bedrock on the north mountain area, and in the south massifs the pre-Neogene rocks (Fig. 2) (IGME 1994, 2005; Bidakis and Athanasoulis 1994).

It is the nappe emplacement and post emplacement tectonic and depositional history of the Messara which formulated the present day hydrogeologic structure of the Messara basin. The main aquifer of the basin is the quaternary deposits, which fill the plain area, and which are the main water resource of the Messara valley (Fig 2). Aquifers of lesser importance, relative to water potential of alluvium, occur at the Gergeri karstic spring on the north and the isolated karstic aquifers on the Asteroussia chain mountain, which both host better quality water (Knithakis and Kalogianakis 1992; Perleros et al 2003).



Figure 3. Sub-basins of the main aquifer system of Messara (alluvial deposits and Pleistocene conglomerates). Red dashed lines delineate covered faults; red solid lines delineate faults mapped by IGME; blue lines delineate isopiezometric contours (in meters asl)

The lithological structure of the alluvial basin has been constructed by evaluation of more than 400 well-logs, the results of FAO, and geophysical surveys, wherein the covered faults by alluvium were delineated. Since faults are invisible, their locations were determined by elaboration of well-logs in correlation with the geodynamic model of the region (Fig. 3). It is observed that the Messara alluvial basin is numerous downthrown blocks of different elevations within the Messara graben, and locally, erosion troughs across the main course of rivers were formed, above which the Pleistocene and the alluvial fill varies in its thickness and composition accordingly. The alluvial

basin is encompassed by the higher elevation of adjacent blocks of practical impervious rocks. Within the alluvial basin, the smooth valley bottom conceals blocks of different hydrogeological properties and can be described as consisting of ground water sub-basins of different extension, shape, and depth, which are separated by practical impervious rocks, resulting from the relative movement of blockfaults (Figs 4a,b,c). Thus the alluvial basin itself is not a uniform hydrological unit, which can be subdivided into three sub-basins in the mean of E-W direction with different hydrogeological properties, named: Moires, Bagionia- Asimi, and Xarakas (Fig 4a). The relative higher elevation of middle blockfault (Bagionia) causes the ground water to move in opposite directions. Furthermore for the purpose of the study, in particular for the groundwater simulation, the basin has also been subdivided into 28 parts for morphological, geological and hydrogeological reasons.

The Alluvium deposits cover an area of 156.7 km², while Pleistocene deposits (conglomerates) cover an area of 62.6 km^2 . The total water volume of alluvium gravelly-sandy material representing a good aquifer is about 249 Mm³, calculated by the detailed structure of the basin and assumed storage coefficient (S) 8%- 10%, which are close to field data. Similarly, the total water volume of Pleistocene is estimated at 255 Mm³ assuming S-value 5% - 6%, excluding the Pleistocene of Xarakas sub-basin as it was considered as practically impervious.

The existing monitoring system consists of 49 observation wells (Fig. 3) established in 1980 by the Land Reclamation Service (YEB 2005), in which two records per year of the water level were measured: in April (peak level of wet period) and in October (minimum water level of dry period). Downstream of Geropotamos River, the alluvium was under artesian conditions and furthermore, until the period of overexploitation (1984), the rising of the water table secured the perennial downstream river flow for both Anapodaris and Geropotamos River. The hydraulic gradient (i) of alluvium varies between $3.9^{\circ}/_{oo} - 7.2^{\circ}/_{oo}$ and i-values are increased from centre to margin, while the i-values of Pleistocene are steeper, which vary between $16.3^{\circ}/_{oo} - 26.4^{\circ}/_{oo}$.

The specific capacities (Qs) of water wells of alluvium widely vary between 5 - 100 m³/h per m drawdown and from margins towards the center along the main river course, respectively, whereas the Qs-values of Pleistocene vary between $0.8 - 1.5 \text{ m}^3$ /h per m drawdown. The transmissivity (T) has been evaluated from pumping tests, which reflects the outstanding properties of the alluvium. T-values of alluvium aquifer widely vary: around 4320 m²/day in the central-western area of Moires, around 320 m²/day in the eastern area of Moires, from 27 to 334 m²/day in Bagionia, and from 14 m²/day (north area) to about 3300m²/day (central - south area) in Xaraka. In general the marginal alluvium areas and the Pleistocene have limited permeabilities reflected by T-values which are about one order of magnitude lower than those mentioned above (FAO 1972). The Storage coefficients (S) have been evaluated from pumping tests of the order of 10⁻² to 10⁻⁴ and indicate that the aquifers are generally confined at least in those layers at a greater depth. S-values were found in the alluvium to reach 20% locally, but high percentages of clay and silt layers suggest average S-values of 8% -10%. The average S-values in the Pleistocene aquifers were estimated to be about 5.5%.

3.3 Water quality

The quality of groundwater and surface water collected from Messara and Anapodaris basin was assessed by using the criteria given by the water Framework Directive (WFD) and the Dir. 98/83/EC (Kritsotakis and Martinou 2008). Kritsotakis and Martinou (2008) reported that concentrations of physico-chemical parameters, heavy metals, conventional pollution parameters, total organic carbon and phenols as well as pH and electric conductivity values of karstic aquifer groundwater samples did not exceed the Parametric Values given by European Community. In shallow aquifers (alluvium), groundwater samples contents over the drinking water guidelines given by Dir. 98/83/EC have been recorded for the following water quality parameters: nitrate and sulphate evidencing contamination sources such as fertilizers, wastewater disposal sites and olive-mill factories. Although, all parameters of pesticides, which in the last 50 years were used in the

area, were analyzed, only the aminomethylphosphonic acid (AMPA) which is the major metabolite of glyphosate, was detected in the ground water samples in values close to the parametric one. Furthermore, the analysis of surface water (stream flow) occasionally showed anthropogenic contamination with high value in parameters sulphate and chloride mainly due to agriculture



Figure 4a.. East – West cross section of aquifer system of Messara (location on fig. 3; vertical scale meters a.s.l)



Figure 4b. SSW- NNE cross section of aquifer system of Messara- Moires area (location on fig. 3)

Figure 4c. North- South cross section of aquifer system of Messara - Xarakas area (location on fig. 3)

4. DATA ANALYSIS

4.1 Precipitation

Daily rainfall data has been recorded at 23 meteorological stations (Fig. 2) and a 32-year long time series (time period 1973 - 2005) was used in the analysis (YEB 2005; EMY 2005). The precipitation indicates intense spatial and temporal variation. The average annual precipitation at

the MT35 station located at an altitude of 150m above sea level (asl) is 511 mm, while at IDH 2 station located at 1,450m asl on Psiloritis mountain it is 1,647 mm. The irregularity and orientation of the isohyets on the mean-annual-precipitation (Fig.1) indicate orographic effects (Linsley et al 1988). The lapse rate on the north part of the basin was calculated at 91 mm per 100m in altitude using linear correlation of annual precipitation (r=0.97); while on the south part 25 mm per 100m altitude (r=0.83).

The average annual precipitation over the Messara area was calculated for the period 1973-2005 and for the wettest and the driest observed year. Given that the distribution of stations is nonuniform and the geomorphological relief effects precipitation, three methods were applied: Thiessen, grid-point, and isohyetal. The resulting values differ less than 1% among the above methods and the average annual precipitation was calculated at 669 mm, in the driest year (1989-1990) 390 mm, and in the wettest year (2002-2003) 1,200 mm. It should be noted that no trends are observed in the statistical analysis of a 32-year-time series to certify reduction in annual precipitation, as for example is observed in Cyprus.

The statistical analysis of a 32-year long series shows that the annual precipitation conforms to normal distribution, as the statistical parameters of data sets a "fitted" well and it was also tested with chi-square and Kolmogorov-Smirnov goodness of fit. Fig. 5 shows the probability of annual precipitation. It is observed that the precipitation of 990mm in the wet year 2002-2003 and of 370 mm in the dry year 1989-1990 both have a return period >100 years. The analysis of monthly precipitation shows that the wet months (November – April) conform to a three-parameter gamma function (Pearson III), whereas none function is fitted on dry months as precipitation is almost or equal to zero. The monthly distribution of certain probabilities is shown in Fig. 6, in which it is observed that 75 per cent of the precipitation falls within four months (November-February) in a normal year and the percentage increases towards the dry year.



Figure 5. Return periods of annual areal Precipitation of Messara sub basins for various levels of probability

Figure 6. Monthly Precipitation for various levels of probability of Messara plain

4.2 Potential Evapotranspiration (ET)

Climate data have been recorded at seven meteorological stations since 1973. Monthly potential evapotranspiration rates were estimated, with HYMOS (1999) hydrological database, applying the methods Penman, Penman-Monteith, and pan evaporation using readily available climatic data of a 29-year long time series: air temperature, relative humidity, wind speed of height 2m, cloudiness, class A pan evaporation and also vegetation characteristics of the close environment of the station. The estimated ET values widely vary between the above methods. In particular, the Penman method compared to the Penman-Monteith overestimates ET by 43%-67% per year, whereas the pan method compared to the Penman-Monteith underestimates ET by 10%-27% per year. Furthermore, the yearly ET of a station, which is estimated with the Penman method, shows significant differences among years (ranged 8%-65%) as well as with the pan method (5%-26%), whereas the

yearly ET of the Penman-Monteith method shows no significant difference (8%-12%) among them (Fig. 7). Additionally the pan values in some years show a different trend compared with the other two methods. It is considered that the Penman- Monteith method provides accurate estimates of ET in the study area, which is also recommended by FAO (1998) as a sole ET method to determine reference evapotranspiration and it is in agreement with pertinent studies (Bertaki et al 2000).

The average annual ET at seven stations estimated with the Penman- Monteith method for the period 1973-2003 varies from 1,238 to 1,457mm, and the lapse rate is calculated at -42.4 mm per 100m altitude, using linear correlation (r=0.95). Within the annual cycle, the monthly ET rate changes from about 25 mm in winter to 225 mm in summer.

The estimated ET time series (32-year long) have shown gaps in short periods, resulting from the absence of concurrent data of meteorological parameters, in particular wind speed values which show insufficient relation between stations. The gap in the time series of ET was filled in applying the empirical formula: $E=(\alpha R_a-b)/(1-cT)$ (Koutsogiannis, 1997) where: E= the mean monthly ET, Ra=extraterrestrial radiation expressed in equivalent evaporation in mm/day, T=mean monthly temperature, α ,b,c= coefficients which could be calculated using least square method between estimated data ET and T. This method resulted in relatively accurate results tested in the period 2002-2005 with readily available data.



Figure 7. Estimated potential Evapotranspiration of Messara stations, in mm per year, with Penman method (dashed lines) and Penman-Monteith method (solid lines)

5. SURFACE WATER MODELLING

Streamflow data were initially examined for possible errors resulting from instrumental or observation deficiencies. The analysis of location of stations showed that error in time series could possibly exist resulting from the change of slope or dimensions of river bed and the malfunction of instruments. Human modification of stream flows during a period with a consequential change of the volume or the flow of the river, is an additional reason to produce changes in time series. The consistency of time series were examined using the double mass curve (DMC) method of each streamflow time series (Qs), versus a synthetic streamflow time series (Qp) estimated from the areal precipitation (P) of watershed of the station and by the form Qp=kP (where k is calculated from the correlation between observed annual data Qs and P), instead of applying DMC to stream flow between time series of runoff, given that the last shows the relevant change and it is impossible to determine the specific curve of inconsistency (Fig. 8).

The curves indicate that the time series of the two stations have inconsistencies, where the investigation showed that they resulted from human interference, in particular from the construction of a small reservoir (0.25 Mm³) in the Lithaios catchment and additionally for the Festos station by an increased infiltration rate resulting in the depletion of the water table in the main aquifer system. The time series analysis using DMC determined the time when essential changes of the hydrologic circle of the basin occurred. Two periods have been distinguished: (1) the period 1986-2005 where a steady decrease of the runoff at Festos station was observed, from a perennial downstream flow of 29 Mm³/year to intermittent flow less than 5 Mm³/year. Simultaneously an increased infiltration rate was observed as the water table of the quaternary aquifer system declined up to 45 m in depth. Those changes in the hydrologic circle occurred due to over pumping of the aquifer system by a large number of water wells. The same situation to a lesser extent was also observed in the Anapodaris- Xarakas basin. (2) The period 1973-1986 which is characterized with a perennial flow of rivers and with a limited water exploitation was restricted into small areas close to the outflow of springs or in the segment of streams with a permanent flow.



Figure 8. Double mass analysis of measuring vs generated annual runoff data at Festos gauge station (slopes indicate human interference to hydrologic regime)

The semiarid climatic conditions, the moderate significant correlation of precipitation- runoff, the complexity of the basin, the human interference in the runoff process (groundwater abstraction, impounding water into a reservoir) and the existing data were driven to apply to the explicit moisture accounting model Sacramento in a monthly time step, which is a lumped conceptual model. The modified Sacramento model (Burnash et al 1973) has also been used in pertinent studies in Crete showing that it can simulate the rain-runoff process (Tsanis and Apostolaki 2009). The model components (estimation of parameter values) relied on the conceptual model, in particular on analysis of the relative parameters of the basin, hydrograph, and human interference on the hydrologic regime.

The model was calibrated manually with a "trial and error" method using two curves: (1) the typical simulation through comparison of monthly runoff volumes of simulation and observed values and (2) the comparison of accumulated monthly volumes which indicates the capability of the model to predict the runoff volume. Since the parameters of the hydrologic circle of the basin had changed in the above mentioned periods, in conjunction with the constraints of the model for changing the parameters during the simulation period, the model was calibrated into two periods, 1973-1986 and 1986-2003. The optimized set of calibrated parameters is within the range suggested by the model's users in particular the representative one for the climatic conditions of the area and the achieving indexes were: explained variance >0.835, efficiency >0.914, and r>0.997.

Basin	unit	Precipitation	Potential ET	Actual ET	Runoff	Infiltration
Plakiotisa (Anapodaris) (simulation period 1974-1994)	mm	703.6	1320.6	504.4	153.0	46.2
	Mm3	50.9	95.6	36.5	11.1	3.4
	% P	100%	187.6%	71.7%	21.7%	6.6%
Lithaios (simulation period 1973-1987)	mm	912.2	1285.1	615.2	189.6	107.9
	Mm3	<i>39</i> .8	56.1	26.8	8. <i>3</i>	4.7
	% P	100%	140.9%	67.4%	20.8%	11.8%
Lithaios (simulation period 1984-2003)	mm	912.3	1323.9	617.2	127.4	167.7
	Mm3	39.8	57.8	26.9	5.6	7.3
	% P	100%	145.1%	67.6%	14.0%	18.4%
Geropotamos- Festos (simulation period 1973-1986)	mm	710.8	1308.4	593.1	72.4	45.2
	Mm3	284.6	523.9	237.5	29.0	18.1
	% P	100%	184.1%	83.4%	10.2%	6.4%
Geropotamos- Festos (simulation period 1989-2003)	mm	672.5	1357.5	565.6	13.6	93.4
	Mm3	269.3	543.6	226.5	5.4	37.4
	% P	100%	201.9%	84.1%	2.0%	13.9%
Anapodaris (Xarakas) (simulation period 1980-2003)	mm	657.7	1331.8	565.2	54.7	37.8
	Mm3	138.5	208.5	119.1	11.5	8.0
	% P	100%	202.5%	85.9%	8.3%	5.8%

Table 1 Sacramento model results (average values in mm and in Mm3; %P indicates the percentage on precipitation)

The inputs of the model were the areal precipitation and the potential ET and the outputs were: actual ET, runoff, base flow, changes in ground water (GW) storage, GW abstractions, and GW losses. Additionally for those basins without observed data, a runoff time series was generated using the calibrated parameters of the model. Table 1 depicts the average annual values of the hydrologic circle of basins, in mm and Mm³. It is observed that in the Anapodaris-Xarakas basin the runoff coefficient (CR) is estimated at 0.083, and the infiltration coefficient (CI)=0.058, and actual ET is estimated at 565.2 mm compared with 1331.8 mm of the potential one, which represents 85.9% of the areal precipitation. In the Geropotamos basin CR changes from 0.102 to 0.02, the CI changes from 0.064 to 0.139 for periods 1973-1986 and 1989-2003 respectively, due to the above explained reasons, and the average actual ET (1989-2003) is estimated at 565.6 mm compared with 1357.5 mm of the potential one, which represents 84.1% of the areal precipitation.

6. GROUNDWATER MODELLING

The groundwater conceptual model relied on the hydrological, geological and hydrogeological analysis which is summarized in the previous paragraphs. The inflows to the groundwater basin are the infiltration of precipitation, from the stream beds, and the return irrigation. Additional artificial recharge trough open canals located parallel to the main course of the Geropotamos in the SW portion of the Moires basin are applied, the effective capacity of which is considered very limited at least for half of the project as it operates in the area of an artesian aquifer. The spring flows, the seepage into river channels, the pumping of wells and the evapotranspiration are the outflows of the ground water basin. In particular the ground water outflows are restricted into two very narrow zones in the Festos and Xarakas areas (Fig. 1).

Two periods have also been distinguished for the groundwater study: (1) the early period which is characterized with the perennial flow of rivers and the minor exploitation of aquifers and (2) the intense period which is characterized with the overexploitation of the aquifer and the dryness of rivers at least during the summer period.

The modular three-dimensional finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh 1996), was implemented for the simulation of the basin and as interface for pre- and post- processing of data and results of the Groundwater Modelling System (GMS 2000)

were used. The model boundaries were determined by the physical boundaries of the basin, which were defined as "no flow" except for two zones located at Festos and Xarakas wherein ground water flow out of the basin is observed. The area is discretized as two layers with a uniform grid 500m X 500m of 28 rows by 89 columns (4984 cells). In z-dimension the actual elevation of surface and bottom layers were defined by using the "true layer" approach of GMS. The uppermost layer represents the alluvium that is under unconfined conditions and the second layer represents the Pleistocene that is under confined condition. Since the hydraulic conductivity (K) is in many cases the most critical and sensitive modelling parameter, the realistic K-values obtained by pumping field tests were used in the design of the model. Furthermore, due to its anisotropy of alluvium aquifer, 24 zones were distinguished and the mean K-value of each zone was applied (Fig. 9).

The boundary conditions were described using the following four MODFLOW packages: (1) Drain package for the ground water losses of the basin in the Festos and Xarakas zones, in which the conductivity was calculated at 50.2 m/day. (2) Recharge package was applied to the uppermost layer, which was used to simulate the rain recharge, the return irrigation, the spills of absorptive sinks of villages, and the stream bed infiltration with the following coefficients respectively: 21% of areal precipitation for alluvium outcrops and 19.3% for Pleistocene outcrops, which were estimated from the results of the Sacramento model and are close with ones estimated by pertinent studies (Paritsis 2000); 8% of crop irrigation, as drip irrigation method is applied (Panoras, 1999); 80% of the domestic water consumption; 36% of streamflow of surrounding basins entering the aquifer (exclusive of Lithaios and Plakiotissa) in the period of overexploitation, which was calculated from Sacramento results. (3) Stream package was applied in the main course of "Lithaios River" and "Plakiotissa River", which both have a relatively high potential (fig. 2). The leakage of river beds was calculated as follows (Fig. 9): for Geropotamos' segments in the early period between 0.8-2.3 m^{3}/day per meter length (FAO 1970); while in the intense period (2003-2005) between 2.5-8.2 $m^{3}/day/m$. For Anapodaris segments between 0.6-3.1 $m^{3}/day/m$, in both periods as the stream courses the NE boundary of aquifer. (4) Well package was used to simulate the pumping rate of wells (Q). Since the Q are unknown, it was estimated with the following two methods: First, it was estimated from the energy consumption of wells, which in pilot wells the ration of pumping volume per energy was calculated between $1.75 - 2.15 \text{ m}^3/\text{KWh}$, and consequently, the total annual pumping volume was estimated between $37.5 - 45.8 \text{ Mm}^3$. Secondly, the annual pumping volume was estimated between 31.8 Mm³ - 47.7 Mm³ with a scenario that was based on 8 - 12 hours per day operation of wells for a six month irrigation period plus the other uses. The hydraulic heads of field data, as elaborated in the hydrogeological analysis, were used in the model for initial condition.

The model was primarily run in steady state conditions for the two distinguished periods and was calibrated using a "trial-and-error" method for both the hydraulic heads of 49 piezometers and the water budget in comparison with values of the conceptual model. The available data were categorized according to their uncertainty, in those where field data existed such as conductivity, hydraulic heads, geometry of aquifer, and those of no field data were available such as the pumping rates. Since in the early period of exploitation pumping rates were relatively very low, the calibration was done by a slight change of the hydraulic conductivity, which was close to mean K-value of each zone of the conceptual model. Then, the model was tested in intense steady state condition, that was the overexploitation of basin, which showed that it could simulate the stresses upon the ground water potential (r>0.99). In steady state conditions, the conductivity of streambed and the resulting infiltration rate were also calibrated according to field data.

Finally, the model was run in transient conditions. The simulation period was 25 years in monthly steps and the reference time was defined in September 1980 and 300 equal stress periods were set up. For simulation the Block Centered Flow Package (BCF2) was applied and the Preconditioned Conjugate – Gradient 2 (PCG2) method of Modflow-solver was used. The computed heads from the calibrated steady state flow model were used as starting heads for transient conditions. The calibration of the model was achieved by changes in only the pumping rate values of 24 zones, as estimated in the conceptual model. The calibration was done with a trial-and-



error method for 49 piezometers resulting in a significant correlation (overall r=0.994) (Fig. 10 and Fig. 11)

Figure 9. Horizontal hydraulic conductivity (K) in m/day of alluvial zones of aquifer system of Messara (above) and infiltration of stream beds(I) in m²/day per meter of stream length (below). Numbers on figure refer to calibrated K-values and I-values.



Figure 10. Groundwater level variations at well GM3, Comparison of Observed (blue line) to simulated (red) heads.

Figure 11. Observed vs computed heads in transient

state conditions of Messara aquifer system

150

Observed (in meters asl)

Transient state conditions

Observation wells of Messara aquifer

Bagionia

100

Moires

aquife

50

0

aquifer

Xarakas

Aquifer

250

300

 $R^2 = 0,9874$

200

The general results of the ground water simulation are as follows: The complex aquifer system of the Messara basin is characterized with hydraulic interconnected aquifers of two layers with hydrolithic anisotropy. The ground water watershed was determined about the surface watershed of Geropotamos and Anapodaris, which changes depending on pumping rates either side. The ground water flow lines were about the surface stream network system in early exploitation of the basin, while they substantially differ in stress periods where a convergence of flow lines in the center of the Moires and Xarakas basins were observed as a consequence of the locally increased pumping rates (Fig. 12).

The average annual ground water potential in the period 1983-2002, which is considered representative according to the statistical analysis of precipitation, since year 2002-2003 is excluded (return period >100years), was as follows: 47.5 Mm^3 inflows; 57.3 Mm^3 outflows; 9.8 Mm^3 decrease of groundwater storage. The inflows of the main course of Geropotamos were found between 1.5 Mm^3 (90m³/m length) - 4 Mm^3 (240m³/m) in dry and wet years respectively, whereas

the inflow range of the main course of Anapodaris was around 1 Mm^3 ($84\text{m}^3/\text{m}$). The annual out flows in the course of the stream bed of Geropotamos in the early period was calculated as 26.7 Mm³ (875m³/m) while in the intense period it was calculated between 0.4 Mm³ (13m³/m length) in dry years and 5.5 Mm³ (90m³/m) in wet years. Similarly for Anapodaris the outflows were calculated in early period 11 Mm^3 (572m³/m) and for intense period between 0.6 Mm^3 (31m³/m) – 3.2 Mm^3 (166 m^3/m). The ground water outflow of the Festos zone to the neighboring Tympaki aquifer was calculated between 1.3 Mm³ and 0.7 Mm³ in early and stress periods respectively, following the decline of the water table. Similarly, in the Xarakas zone the outflow was 0.9 Mm³ -0.6 Mm³. The average annual pumping volume was calculated at 50.8 Mm³, which shows an over pumping of 9.8 Mm³ from the storage of aquifer representing 19% of the renewal volume and that situation would be stressed more in the near future, as new wells were drilled in 2007 at a remarkable increase of 60%. The allocations of pumping volume among sub basins are (in Mm³): 27.3 for Moires, 1.2 for Galia, 11.6 Bagionia-Asimi, 10.7 for Xarakas. The annual pumping rate significantly varies between 6 Mm³ in the early period and between 14.3 Mm³ - 75 Mm³ for the stress period in wet and dry years respectively, which shows a significant correlation with precipitation (r=0.81), as 98% of the pumping water was supplied for agriculture. The average ground water storage was reduced 9.8 Mm³ mainly from the alluvial aquifer. The annual change in storage was calculated between: reduction 33.3 Mm³- increased 36.7 Mm³ for dry and wet years respectively. It should be noted that in the "extreme wet year" 2002-2003 the storage of the basin increased about 78 Mm³, which represents a refilling of about 8 years average reduction rate of storage.



Figure 12. Modflow results, transient state conditions – above April 1984; below April 2000 (blue lines indicates isopiezometric contours and red arrows indicates scaled flow lines of aquifer system)

7. WATER RESOURCES MANAGEMENT

The average annual water demand of the area was estimated at 60.9 Mm^3 in year 2004, which was allocated 96.6% for agriculture, 3.2% for domestic use, and 0.2% for industrial supply. The agricultural demand was estimated from the irrigated area with coefficients depending on the type of crops, the optimum irrigation dose as suggested by pertinent studies, and the applied irrigation system (e.g. 25 m³/ha for olive trees, 35 m³/ha for grapes, 65 m³/ha for greenhouses) (Roc 2006).

The irrigated area was 16.263 ha, which represents 56% of the total cultivated (29.109 ha) area. The existent water supply system is based on ground water potential. Two reservoirs are under construction: the Plakiotissa dam located in the northern part of Anapodaris basin and the Faneromeni dam located westerly in the neighboring Tympaki basin. Additionally a diversion of the Platis River is planned, which is located westerly of the Tympaki basin, with a twofold purpose: first to fill the Faneromeni dam, as it has been constructed with a capacity at 1.7 times the average yearly outflow, and secondly for the artificial recharge of the Messara basin (Fig.1).

The framework for the water protection is clearly defined by the water framework directive (WFD) 2000/60/EC and the daughter ground water directive (GWD). The implementation of the WFD follows a stepwise approach including the characterization of river and water bodies, the assessment of pressures and impacts of anthropogenic activities, and an economic analysis. For ground water bodies the determination of reference conditions is crucially important. In particular in the Messara, when reference conditions will define the conditions before exploitation of aquifer systems, which means a permanent downstream flow will occur, then the annual abstracting volume should be restricted in the order of 6 Mm³ and consequently the collapse of the local economy will follow. However, if as reference conditions will be defined the conditions as described in the concept of "maximum perennial yield" (Todd, 1980) that means the maximum quantity of ground water perennial available if all possible methods and sources were developed for recharging the aquifer. In specific for the Messara ground water basin the decline of water table has an induced increase of the average annual infiltration of 26.6 Mm³ to storage during the winter, which then is used during the summer. It is remarkable that all the above mentioned surface infrastructures (dams and diversion) have about the same capacity of additional recharge of aquifer, whereas in contrast they have a disproportional construction cost. The only effect to the environment is that the runoff of the basin has been reduced about 81.4% and the river dried up during the summer. It should be also noted that no special protected area exists in the basin.

Therefore, under the semi-arid climatic condition of the area, the sustainable and full development of water resources of the basin can be obtained only by conjunctive use, which involves the coordinated and planned operation of both surface and ground water resources. The River Basin Simulation Model (RIBASIM 2000) was applied to simulate the responses of the basin and to examine the operational procedures to optimize the water supply obtained from the basin. Thereafter, a summary of two scenarios will be presented in relation to the time horizon, the short term and long term, and the scenario of no action will be also taken into consideration.

Short term management. The good qualitative status of ground water could be achieved applying mainly three measures, which are considered feasible with a relatively low cost, as follows: (1) best management practices in agricultural especially on the application of fertilizer and pesticides, (2) construction of domestic waste disposal units of villages, and (3) the systematic control of disposal lagoons of effluents of olive mill factories to prevent leakage. Every applied measure to alleviate the water stress should set as target the reduction of abstracting volume, in order to achieve good quantitative status, in particular for the Xarakas aquifer a reduction of about 16%, for the Moires aquifer about 19%, whereas, despite the overexploitation of the alluvium aquifer for the Bagionia aquifer, none reduction is suggested as it has a surplus due to potential of the Pleistocene aquifer. It should be noted that, in the very near future, the Moires basin will be provided with about 3 Mm³ from the Faneromeni dam but that quantity will be compensated against the operation of new drilled wells in 2007. In case of full operation of new wells (both in Bagionia and Moires) before the water of the Faneromenis' reservoir is supplied, the reduction of pumping rates should be about 28%.

Long term management. Assuming that no more water pollutant activities will be involved in the region, the measures for achieving the qualitative status should be the same as in short term management. Similarly, the measures for achieving good qualitative status for Bagionia and Moires will be the same as short term, unless the diversion of Platys River will be constructed, which is a relatively high cost project, estimated about 130 million euros. In that case water surplus in the area

will be observed. However, the area of artificial recharge should be based on the structure of the aquifer system and on its hydrodynamic operation, as described above, in order to avoid the disfunction of the existing one. In the Xarakas' basin the recent deficiency of water will be permanently solved following the operation of the Plakiotissas' reservoir

No changes scenario. Despite the measures that have been imposed by Local Authorities for the protection of water resources since 1984, their implementation has faced difficulties mainly due to private wells (92% in total). On the occasion that the estimated reduction of pumping rates, as described above in short term management, are not be achieved despite imposed measures, then in the following years the water table will continually decline and consequently the yield of wells will be gradually reduced from the margins of aquifer towards center. Afterwards the abstracting volumes direct will depend on the precipitation and the abstraction volume will be less than the inflows to aquifer which was calculated between 33 Mm³ to 81 Mm³ for dry to wet years respectively. In the case of a dry year's sequence, the deficiency of water in the region has been estimated in the order of 50%.

8. CONCLUSIONS

An integrated water management methodology was developed for the assessment of water conditions in Mediterranean island environments. It combines surface and ground water simulation models and as it requires only a relatively limited amount of data, is particularly applicable to such environments which invariably face water scarcity problems due to overexploitation.

In Particular, the Penman-Monteith method was found the most appropriate to evaluate the potential evapotranspiration, the Sacramento model to simulate the rain-runoff processes of the basin and to estimate the hydrologic balance, the Modflow model, along with a detailed hydrogeological structure of the basin to estimate the diachronic changes in groundwater balance components, and the program RIBASIM to provide the results for alternative scenarios

This methodology was successfully applied to the Messara basin (Geropotamos and Anapodaris – Xarakas watersheds) in Crete, Greece.

According to the simulation results in the Geropotamos watershed for a period of 15 years (1989-2003) with a mean precipitation (P) of 672.5 mm and a potential evapotranspiration (ET) 1357.5 mm, the actual (ET) is 565.6 mm (84.1% P), runoff 13.6 mm (2% P) and infiltration 93.4 mm (13.9% P).

Similarly, in Anapodaris – Xarakas watershed, for the same simulation period and a mean precipitation (P) of 657.7 mm and a potential evapotranspiration (ET) 1331.8 mm, the actual (ET) is 565.2 mm (85.9% P), runoff 54.7 mm (8.3% P) and infiltration 37.8 mm(5.8% P).

Current exploitation of water resources is confined to ground water, mainly for irrigation of 16,263 ha, representing 56% of the cultivated land. The average annual water extraction is estimated to be in the order 50.8 Mm³, thus exceeding the calculated basin yield by 9.8 Mm³ thereby causing a significant lowering of the water table. This in turn causes in the increase of the infiltration rate, which results, on average, in an additional water storage of 26.6 Mm³ per year.

The sustainable and full development of water resources of the basin can be obtained only by conjunctive use of surface and ground water. However, the stresses on groundwater resources following the dam's operation (Plakiotissa and Faneromeni) will be remaining, while the problem will permanent be solved with the diversion of the Platis' River. Otherwise, a significant reduction in water extraction is needed to ensure a sustainable water use as well as compliance with the pertinent WFD regulations.

This methodology will hopefully assist in the implementation of the EU directives, WFD and GWD, for a common EU water policy. However, it should be noted that since simulation models employed utilize a limited amount of data, yearly updates are considered necessary.

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