STOCHASTIC MODELING OF THE KARSTIC SYSTEM OF WESTERN APOKORONAS IN CRETE

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ABSTRACT

Sustainable exploitation of water resources of a karstic system requires a good understanding of water resources potential, the quantitative and qualitative fluctuations of their hydrologic diet as a function of time and space and the region's hydrogeologic conditions. Kiliaris River is located in the Prefecture of Chania and is supplied by quantities of water that emanate from the karstic system of White Mountains. The Stilos springs are considered as the major discharge points of the karstic system of western Apokoronas and one of the main water sources of Kiliaris River. The objective of this work was to conduct a hydrogeologic analysis of western Apokoronas karst and to develop a stochastic model of Stilos springs that can be used as a predictive tool of summer river low flow.

1. INTRODUCTION

The development of rural areas in Greece is closely connected to agriculture and depends on the sustainable exploitation of their water resources. Many rural areas have faced rapid land use changes in the last few decades (mainly agricultural to tourism) that lead to further stresses on their water resources. During dry period, there is lack of water due to different factors such as: droughts, extensive evapotranspiration, water abstraction, high irrigation demand, overexploitation of groundwater and large vertical water exchanges (downwelling into alluvial aquifers) [1,2]. Future increases in water demand are likely to add further pressure to stream ephemerality and quality, with increased upstream abstractions reducing the flow and downstream effluent discharges enhancing its pollution loads. Baseflow of rivers and streams during the summer originates in many areas of Greece from karstic spring water. In these areas, water abstraction from the karst is closely related to low flow conditions in the river, which in turn affects the ecological quality of the rivers [3].

The objective of this work was to conduct an analysis of the hydrogeologic data of the karst system of western Apokoronas and to develop a stochastic model of spring discharges to be used as a predictive tool of summer low flow conditions in the river. Stilos springs are one of the main water sources of Kiliaris river and (in addition to Armenoi and Zourbos springs) are the major discharge points of the karst system of White Mountains in western Apokoronas. Sustainable exploitation of water resources of a karstic system requires a good understanding of water resources potential, the quantitative and qualitative fluctuations of their hydrologic diet as a function of time and space and the region's hydrogeologic conditions.

2. METHODOLOGY

The watershed of Kiliaris River is located in the Prefecture of Chania (15 km east of Chania) and is extended from the top of White Mountains up to the coastal area of the Municipality of Armenoi [4]. The watershed of Kiliaris River includes 8 municipalities. The total catchment area is 130 km^2. The watershed is supplied by quantities of waters that emanate from the karstic system of White Mountains. Stilos springs are considered as the major discharge points of the karstic system of western Apokoronas and one of the main water sources of Kiliaris River. The total length of Kiliaris River is about 36 km. Kiliaris River has four tributaries. Two of them are temporary rivers (Keramiotis and Anavreti). The other two are: Milavlakos and Mantamas. The climate of the region is semi-arid, characterized by precipitation and snowfall (at high altitudes) in winters and hot-dry summers in which evaporation exceeds precipitation and results in significant water deficit. The watershed has a significant rainfall variation. The mean annual precipitation in the northern part of the catchment is 705 mm (low elevations), while in the southern part is 2125 mm (mountainous zone). The catchment's slope varies between 43% at the foot of White Mountains and 4.8% at the estuaries of Kiliaris River. The highest catchment's altitude is 2041 m at the White Mountains (Figure 1).

The geologic formations of the region are presented in Figure 2 [5]. These are:

A. Limestone of White Mountains - It is found in the centre of the prefecture. The annual flow in the northern part is $500*10^6$ m^3. The total area is 850 Km^2 and the average rainfall is 1700 mm/yr.
B. Schists (phyllites-quartz) – Schists are found in the western part of the prefecture. The total area is 500 Km^2 and the mean precipitation is 700 mm/yr. The total hydrologic potential of the area is $300*10^6$ m^3/yr.
C. Neogene and quaternary deposits - These deposits are found in the northwestern part of the prefecture (Kissamo, northern Plain of Chania, Skine, Fourne, Alikianou, Vatolako, and the northern part of the catchment of river Koiliaris). In these regions there are underground reservoirs with important, but unquantified reserves.

Stilos springs discharge at 17 m above sea level and have intense seasonal fluctuation in their discharges. Mean annual discharge of Stilos springs is $68*10^6$ m^3/yr (hydrologic years 1970-2001). 89% of the total flow is found in the November-June period. There is evidence that the springs have both regulating reservoir of water and permanent reservoir of water. The existence of the springs is due to the interception of underground flow of water from the karstic aquifer with the Marls in the Neogene deposits (due to tectonic contact). The operation of the springs is characterized by the influence of rainfall (rapid discharge), and by the time delayed discharge.

The study was divided in two parts, the analysis of the historical monthly hydrogeologic data and the analysis of recent continuous data. In the first part, all available hydrogeological data and GIS information were used to clarify the operation of the karstic system in consideration. The objective was to illustrate the correlation between water level fluctuation in the karst and spring discharges. An analysis of the continuous data was conducted in the second part of the study. These results would then lead to the development of a conceptual hydrologic model, which considers the karstic system of western Apokoronas as a system of multiple reservoirs. These data were used to develop a stochastic model to forecast minimum, low-flow discharges in the river [6]. There many model/equations, such as Maillet, Tison, Mangin, Schoeller and Boussinesq, that can simulate the recession curve of kasrtic springs [6]. The reason we chose Maillet's model is that it has physical meaning, it is based on the hydrologic balance equation during the recession (no rain) period and it assumes that the spring discharge at discrete points, (which is the case for Stilos springs) and the system acts as a linear reservoir. The statistical formulation of Maillet model [7] that will be used to model the recession part of the hydrograph of the springs, has the following mathematical formulation: $q = -Q_o * e^{-\alpha * t}$. Three different timeseries datasets were used. a) Hydrogeologic data (monthly data for flow and water level) obtained from the Land Reclamation Service of Chania Prefecture, b) telemetric data from one well (Samona) in the karst from the Water Management Department of the Region of Crete and c) continuous flow data of Kiliaris River from the Technical University of Crete.

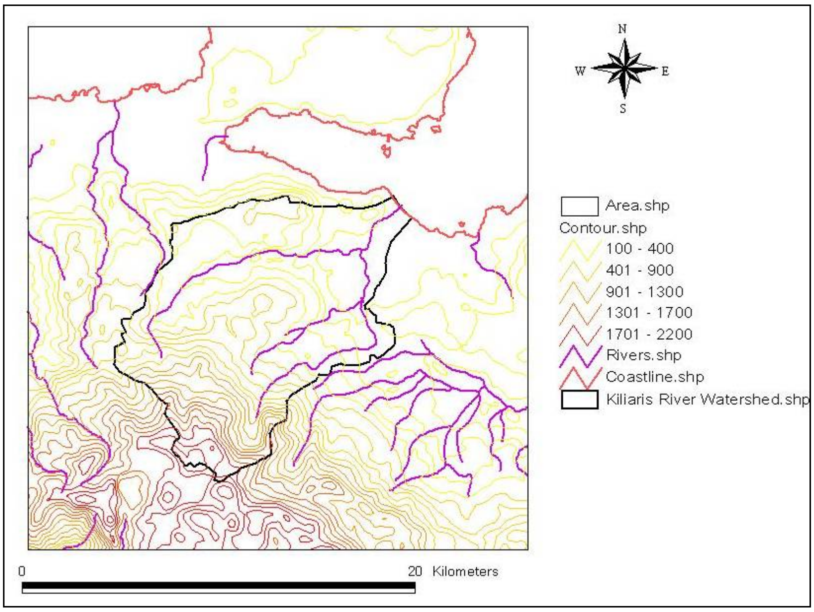


Figure 1. Elevation contour map of Kiliaris River watershed.

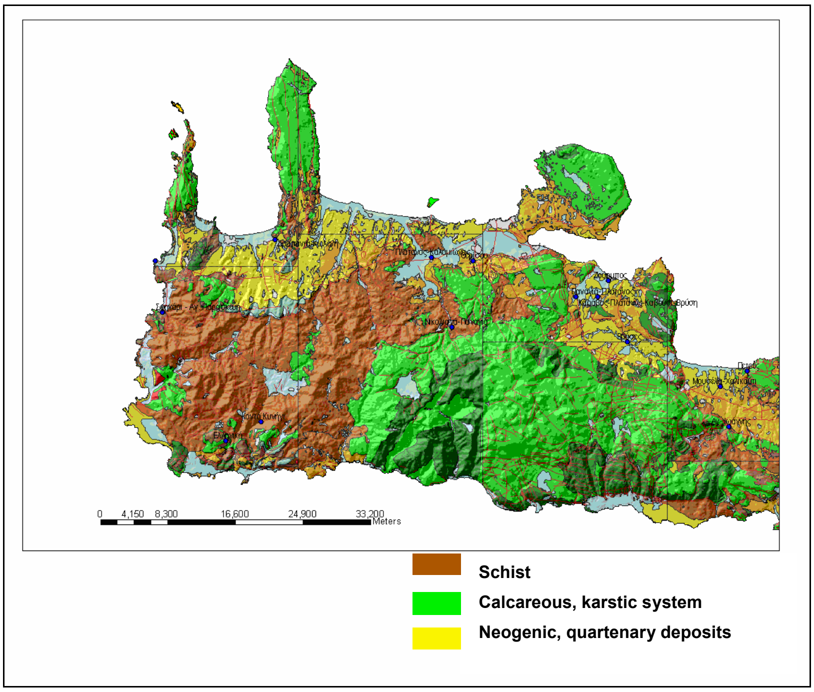


Figure 2. Geological map of the Municipality of Chania [5].

3. RESULTS

3.1 Analysis of Historic Data

Over the period of 1971-04 the Land Reclamation Service of the Prefecture of Chania has been conducting monthly measurements of ground water levels and spring discharges and river flows. These data can be used in the development of a conceptual hydrogeologic model of the behavior of western Apokoronas karst. The groundwater well record that was used in this analysis was the well of Machairi which is located approximately 1 km up-gradient from the springs in the karst.

The annual hydrographs of Stilos springs exhibit features of inter-annual periodicity. Figure 3 represents 7 characteristic hydrographs of Stilos springs discharges in order to illustrate the similarities between annual hydrographs. This analysis was focused on the recession part of the annual hydrographs. The recession rate slope of the hydrographs exhibit low variability. The average value of recession coefficient ‘α’ in Maillet’s model was calculated to be $2.16*10^{-2}$ d^{-1} and the standard deviation was $0.47*10^{-2}$ d^{-1}. In addition, the average relativity ratio between maximum and minimum spring discharges was 12 with a standard deviation of 4.5. The magnitude and variability of the ratio is low indicating that the karstic system has a well developed, interconnected fracture network that has high potential in delivering the groundwater flow. The rate of recession was influenced by the time of the year peak discharge occurred. The highest rate of recession occurred when the peak discharge appears in April indicating increased snow melt conditions.

In addition, the behavior of the springs is consistent with the water level fluctuation of the karstic aquifer. Figure 4 presents a comparison of water levels from Machairi well and discharges of Stilos springs. The correlation between the water levels and the flow using all the available data is quite good (R^2 = 0.73). The correlation coefficient improves when the respective data of the recession portion of the hydrograph are used (Figure 4b). This analysis indicated that the karstic system of western Apokoronas has a well developed fracture network with high flow potential. The system’s discharge response is consistent to precipitation events and water level fluctuations within the karst.

3.2 Analysis of Continuous Data

Monthly data do not capture the temporal variability of the behaviour of a hydrogeologic system. Karstic systems are inherently non-linear and multi-faceted. Continuous measurements enhance our understanding of the system and our ability to develop models that can predict their behaviour. Two continuous datasets were used in this analysis. The flow measurements of Kiliaris River (Agios Georgios station) and the water level measurements of Samona well which is also up-gradient from the springs were used in this analysis. Figure 5 represents the daily flows of Kiliaris river at Agios Georgios station. The flow measured at this station corresponds to the flow of Stilos springs (tributaries of Milavlakas, Mantamas and Anavreti) and the flow of Keramiotis tributary which is temporary. In the hydrograph, one could make the following observations:

1. The hydrograph was characterized with peaks of quick response and of slow response. The quick response was mainly due to surface runoff and the slow response due to spring flow recession.
2. The slow response recession rates of the springs which correspond to spring flow are very consistent. For instance, the recession rate of spring 2004 was similar to spring of 2005 (shown in red circles).
3. The slow spring recession response has two distinct rates, one that corresponds to spring, high flows and another to summer, low flows. The third observation can be substantiated when water levels and flow data were compared for the same period (Figure 6). The comparison indicated a strong correlation (with a 3-day time lag) of water level at Samona well with flow. The

correlation was especially strong for different distinct periods without rainfall. In addition, the spring of Anavreti does not run throughout the year, but only when the flow in the river is high (early to mid December) and stops when the water flow drops in the spring.

The analysis above suggested the existence of "two reservoirs" within the karstic system of western Apokoronas; the upper reservoir with a faster response and the lower reservoir with a slower response. This is due to the fact that the springs are supplied by two geologic formations with different hydraulic characteristics: the Limestones of Tripolis zone (Triassic to Cretaceous period) and the older carstic group of Metamorphic Crystalline Limestones (Paleozoic or Mesozoic**).** The dual response system can be explained through the ability of the karst to release water and represents its hydrogeologic characteristics. The quick response system represents the well developed portion of the karst (large fractures), while the slow response represents the lower porosity, small fractures karst. Hydrogeologic observations suggest that the Limestones of Tripolis zone have a well developed karst and justify the quick response system while the Metamortphic Crystalline Limestones have a less developed karst that justifies the slow response. The spring of Anavreti drains the upper reservoir only, while the fluctuations of water level of the well at Samonas exhibited the combined variability of the upper and lower reservoirs.

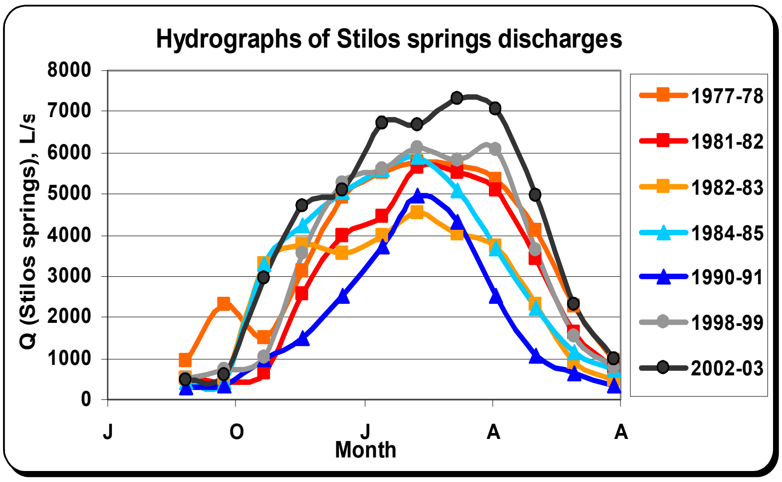
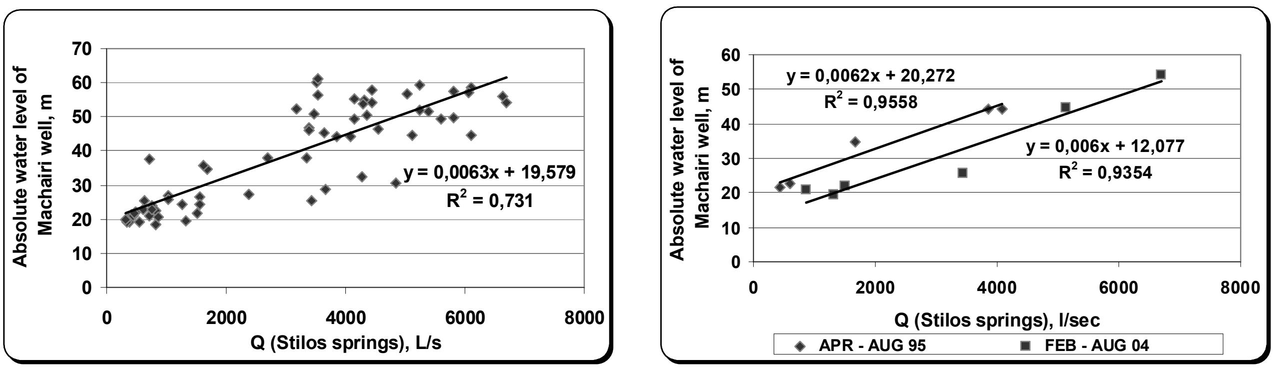


Figure 3. Characteristic hydrographs of Stilos springs discharges for 7 hydrologic years.



(a) (b)

Figure 4. (a) Correlation between Machairi well water level and discharge of Stilos springs using all available data and (b) Correlation between Machairi well water level and discharge of Stilos springs during dry periods (1995 and 2004).

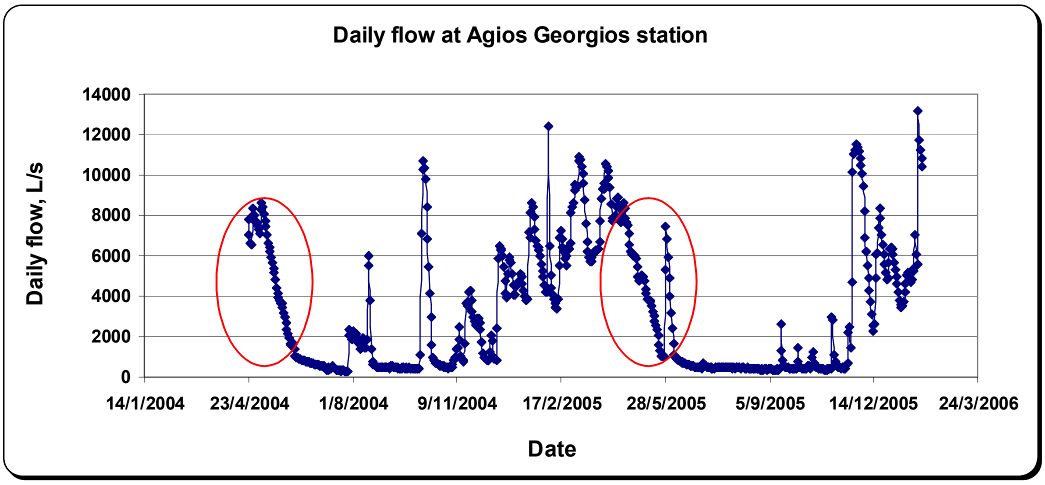
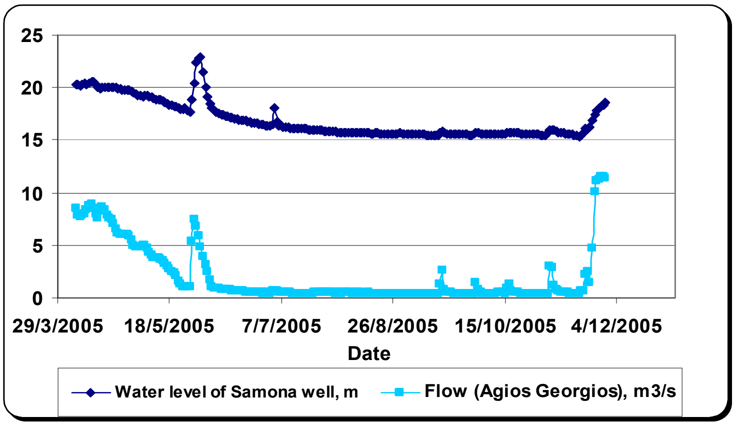


Figure 5. Daily flows at Agios Georgios station.



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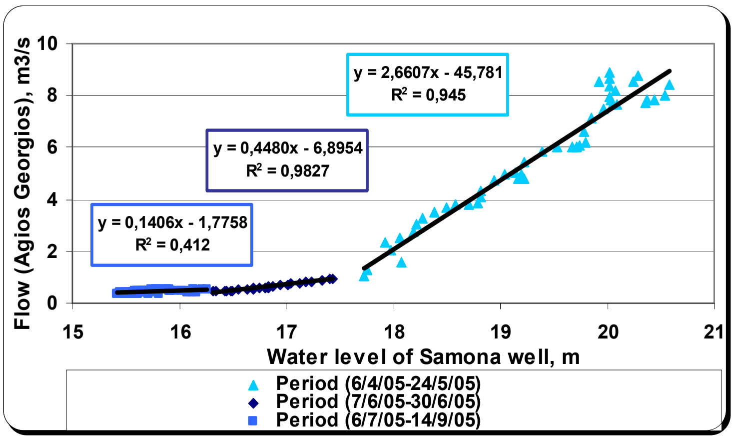


(b)

Figure 6. Comparison of water level (Samona well) and flow (Agios Georgios station): (a) daily fluctuation of flow and water lever and (b) correlation of water level with flow at different time periods.

The previous analysis results in a conceptual model which can be used in the development of a stochastic model of Stilos springs discharges that can be used as a forecasting tool of minimum, low flows of the river. A 'two part' Maillet model was developed representing the upper and lower reservoirs. The model had the following formulation:

$$q_{model} = Q_{oUR} e^{-a_1 t} + Q_{oLR} e^{-a_2 t}$$

Where q_{model} is the total spring discharge, Q_{oUR} and Q_{oLR} are the initial discharge contributions of the upper and lower reservoirs respectively, and $\alpha_1$and α_2 are the recession coefficients of the upper and lower reservoir. The sum of the initial discharge contributions of the two reservoirs is the maximum total discharge of the springs which is obtained from the field data.

The discharges of the dry period of 2004 were used for the calibration of the model and the discharges of the dry period of 2005 were used for the verification of the model. Figure 7 presents the results of model simulation with the field data for the calibration and the verification period. The recession coefficient for the upper reservoir was 0.0996/d and for the lower 0.0261/d. The model had three parameters to calibrate, the two recession constants and one of the two reservoir initial discharge contribution. The remaining initial discharge contribution was estimated by subtracting the calibrated initial discharge value from the total initial discharge which is the maximum discharge of the springs. The parameters were obtained by minimizing the root mean squared error (RMSE) between the field and model data. Once the model was calibrated, the parameters were used to simulate the discharges of the second year. The calibration and verification equations are presented below.

Calibration Period $$q_{model} = 6200.4 \times e^{-0.0996*t} + 2388.4 \times e^{-0.0261*t}$$

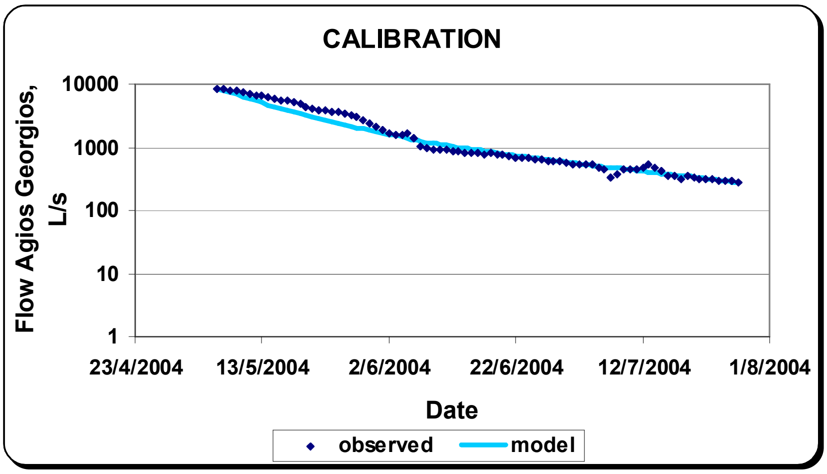
Verification Period $$q_{model} = 5037.3 \times e^{-0.0996*t} + 1939.4 \times e^{-0.0261*t}$$

The ratio of the initial discharges of the lower to upper reservoirs was 0.385. The apportionment of discharge at the time of maximum flow is 72% from the upper reservoir and 28% from the lower. For the simulation period, the lower reservoir contributed 56% of the flow and the upper 44% while for the verification period the contribution was 67% from the lower and 33% from the upper.

The inverse of the recession coefficient represents the hydraulic detention time of the reservoir when there is no rain condition. In that case, it can be shown that 95% of the volume of water within a reservoir can be drained within 3 detention times. The detention time of the water in the upper reservoir in late spring was estimated to be 10 days and 95% of the volume of the reservoir can be drained within 30 days. Similarly, the detention time of the lower reservoir was estimated to be 38 days and 95% of the volume of the reservoir can be drained within 114 days. This is consistent with the field data presented earlier. The volume of water contributed by the upper reservoir appeared to have been depleted by early June. This indicates that if there is no rain during the summer, the discharge from the lower reservoir will be depleted by the end of September. The results highlight the potential for water shortages during extended periods of drought.

4. CONCLUSIONS

The karstic system of western Apokoronas is an autonomous system which can be managed accordingly. The analysis of the system's discharges indicates that the karstic system of western Apokoronas is a system of two reservoirs, an upper- rapidly discharging reservoir and a lower-slowly discharging reservoir. This simulation is consistent with the geologic formations of the region. Spring discharges can be simulated with a stochastic model that can be used as a tool to forecast minimum, low flows of the river and "sustainable" water abstraction capacity. The hydrologic diet of the Stilos Springs was shown to be consistent with time. Continuous hydrogeologic measurements can be used to gain further understanding of the system and refine the forecasting models.



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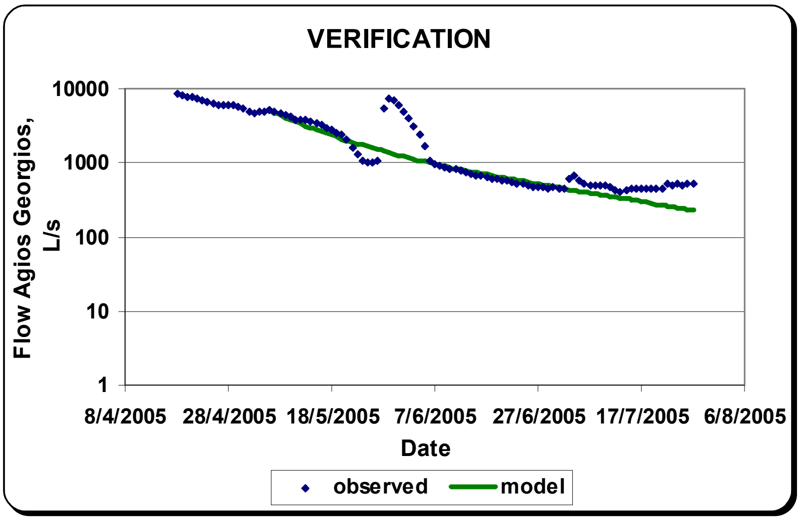

(b)

Figure 7. (a) Calibration (2004 data) and (b) verification (2005 data) of the stochastic model of Stilos springs discharges.

5. REFERENCES

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