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The Aggitis karst system, Eastern Macedonia, Greece: Hydrologic functioning and development of the karst structure

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Summary The Aggitis karst system developed in the marbles of the Rhodope massif. The conditions of the development of its karst drainage network are determined from the geological and geomorphologic settings by means of a microstructural analysis, following Eraso's method. This analysis shows that the karst conduit network intensely developed in the western part of the mountain Falakro where the majority of the open fractures oriented in the same direction as the hydraulic gradient, while the two directions are perpendicular in its eastern part drained by the spring of Drama.

The behaviour of the system was analysed by means of hydrodynamic and water geochemical techniques. Despite the extension of the cave system and of the favourable development conditions of conduits, the functioning appears complex, with a significant storage, and a slow infiltration as well as an easy drainage. On the contrary the Drama karst system, characterised by a low variability in its hydrological and geochemical characteristics does not show any karst functioning.

In the Aggitis karst system the initial groundwater flow conditions in combination with the aperture planes of which the directions are in agreement with the hydraulic gradient, favoured the rapid development of a drainage network system. The recharge from a large

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surface catchment area on non-karstic rocks, through swallow holes in a wide polje contributed to increase the groundwater flow through the karst part of the system, facilitating the development of the conduits.
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Introduction

The quantitative and qualitative evaluation of the water resource and its necessary protection entered in the list of the major priorities these last two decades for many communities. This is particularly the case in Mediterranean countries where the climatic conditions, associated with the increasing demand for water supply, involve an increase in the exploitation of the resource. This situation made us to reconsider the possibilities offered by the karstic aquifers. Indeed, the very complex structure and the reputation of its high vulnerability concerning this type of reservoir often limited the exploitation of these resources.

The karstification creates a significant heterogeneity of the permeability within the aquifer where the flows are organized and so create a hierarchical structure, from the surface to the spring (Mangin, 1975, 1985) which allows the coexistence of significant flows with rapid transport in the conduits and slow flows from and/or to wide cavities poorly connected to conduits. This particular structure of voids makes difficult the analysis of the hydraulic behaviour of these aquifers and the determination of the characteristics of their reserves. Their study must be primarily based on the analysis of their dynamic functioning.

Moreover, certain karstic aquifers are recharged by surface runoff on non-karstic impermeable formations. Both parts the karstic aquifer and the non-karstic catchment area drained by swallow holes, constitute the karst system. This situation occurs at the system drained by the Aggitis spring also known as Mara in Eastern Macedonia, Greece (Fig. 1). The spring discharges from the calcareous Falakro massif. According to Dimadi (1988), the karst aquifer has also an allogenic recharge by surface rivers from a large catchment area, geologically very diverse, localised at the north of the Falakro massif, flowing into swallow holes of a wide polje and most likely through the thick and porous alluvium filling the polje. The water of the spring is partly used both for water supply of the neighbouring towns and for irrigation.

According to Ivanov (1988), the Falakro massif uplifted during Miocene; as a consequence it has a very recent continental geological history during which the karst developed. This young karst is an original example that is very interesting for better understanding the conditions of karstification in an active tectonic context. Moreover this study, within the framework of a European project, gave the opportunity of applying a methodology that had proven reliable in France, but had not been used yet for the hydrogeological studies of the karst in Greece.

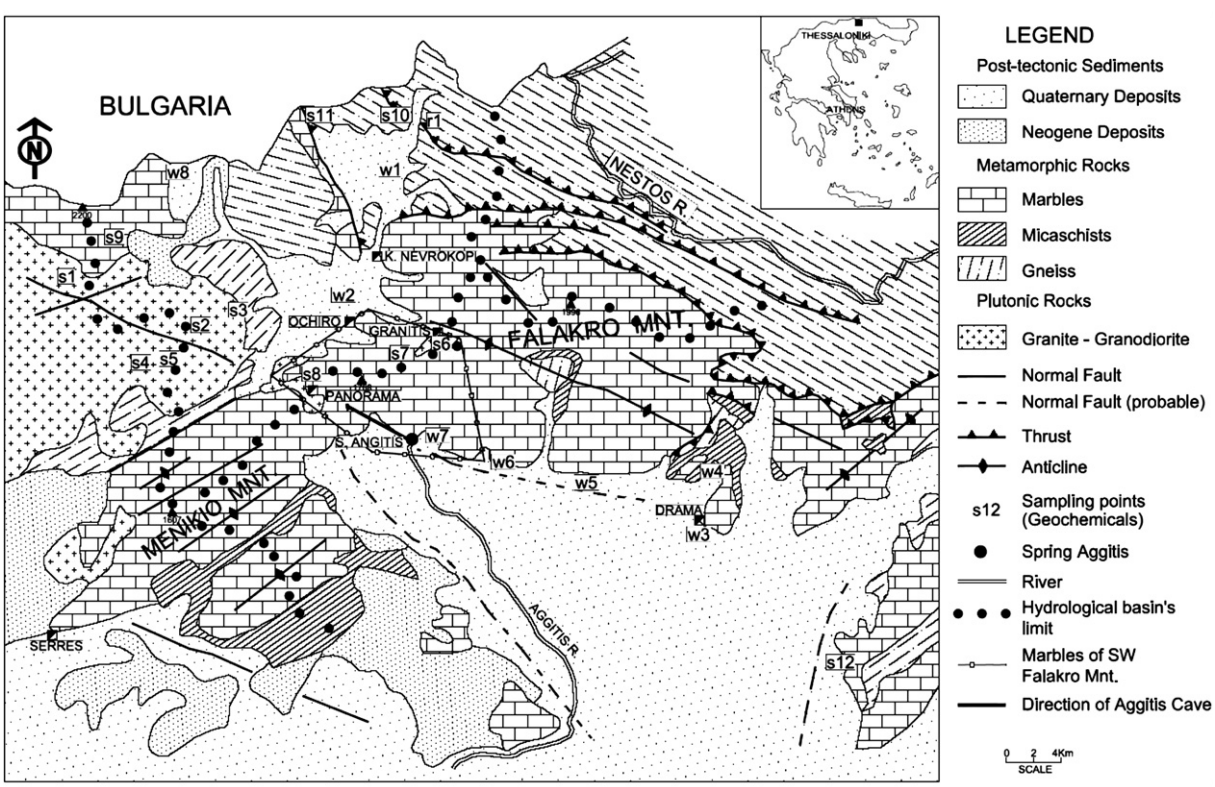

Figure 1 Location of the study area and geological situation of the Aggitis spring.

In order to complete the knowledge already acquired concerning the hydraulic behaviour of Aggitis karst system, three methods of investigation were adopted: (a) the analysis of the framework of the karst development by the interpretation of microstructural measurements, (b) the hydrodynamic analysis of the system, and (c) the study of the natural tracing by the hydrogeochemical approach. The first method deals with the structure of the karst network drainage both second and last ones deals with its functioning.

Geographical and geological settings

The Aggitis spring located at 123 m altitude on the southwest side of Falakro constitutes the outlet of an underground river explored and mapped for about 8.5 km. The mountain Falakro, located at approximately 200 km at the north-east of Thessaloniki, belongs to the Rhodope massif. Its western part covers 103 km^2 culminating at 1768 m altitude. It is limited to the north by the polje of Kato Nevrokopi, to the south by the plain of Drama and to the west by the granodiorite intrusion of Panorama (Fig. 1). The limit between the western sector and the main body of Falakro is underlined by the outcropping granodiorite of Granitis and the valley that is followed by the road connecting the towns of Drama and Kato Nevrokopi.

The stratigraphic column of Falakro (Epitropou and Chagipanagis, 1987; Chagipanagis, 1991) indicates two metamorphic series, a siliceous lower series and a carbonate upper series, the whole being affected by the granodiorite intrusions. The siliceous series comprises a thick unit of more than 2000 m of orthogneiss, overlaid by approximately 300—600 m thick formation of a repetitive alternation of gneisses—micaschists—marbles with intercalations of amphibolites. This series constitutes the impermeable base of the carbonate aquifer.

The carbonate series, approximately 1500 m thick, constitutes the aquifer. It begins with graphitic marbles which base is thin-platy marbles well bedded with muscovite on the bedding planes. The graphitic marbles gradually pass to white, compact, carbonate marbles, that are the principal component of the series. In some sectors, dolomitic marbles appear between the graphitic marbles and the white marbles. The granodiorites of Panorama and Granitis are assumed to be connected at depth; they formed at low temperature, 600—650 °C, so that they did not generate a significant metamorphism but only skarns. The age of the siliceous and carbonate series cannot be defined with accuracy and it is still the object of controversies. Brachiopods found in Bulgaria in formations equivalent to the marbles of Falakro date them to the Devonian (Jones et al., 1992). On the other hand the measurements of $^{207}Pb/^{206}Pb$ in zircons gave to the base of the marbles a Permian age (Dinter, 1994a). Moreover, Greek authors (Chagipanagis, 1991; geological maps of IGME, 1982) generally give to the marbles a Mesozoic age and to the siliceous series a Paleozoic age. For the granodioritic intrusions, the K/Ar dating dates them to Oligocene (Jones et al., 1992). The entire massif could have emerged during Miocene and would be subjected to continental erosion since that time.

From a structural point of view Falakro is an anticline whose axis is oriented 120 °N. The Rhodope massif was affected by several phases of folding, of which the two main phases occurred between the lower Cretaceous and the middle Oligocene. The first phase was compressive with thrusts, reverse slip faults and isoclinal folds whose axes are oriented NE—SW (40° to 60 °N). The second phase is represented by open folds which axes are almost horizontal and oriented NW—SE (120° to 130 °N); this phase is also related to the formation of synclines and anticlines according to the aforementioned direction. The brittle deformation developed during Oligocene to Miocene is related to two families of contemporary faults NE—SW (50° to 60 °N) and NW—SE (130° to 140 °N) with particularly very high dips (67° to 88°). This time of regional uplift is responsible for the present morphology. These faults developed under the same stress regime of the extensional deformation. During Pliocene — Pleistocene to present time, the brittle deformation developed two families of faults, E—W and NNE—SSW. These faults are related to an extensional regime during which the minor principal stress axis ($\sigma 3$) oriented N—S. The NNE—SSW trending faults of upper Pliocene — lower Pleistocene age is the most frequent in the study area (Chagipanagis, 1991). The aforementioned elements of brittle deformations are always parallel to the directions of the ductile deformation elements that occurred before Oligocene — Miocene. The NE—SW, NW—SE and E—W trending faults are at the origin of a system of grabens where the plains are currently localised. The intrusion of the granodiorite was associated to this tectonic event.

Surface and karst geomorphology

The surface morphology of the Falakro massif presents a well developed, presently not active stream bed network. Surface karst landforms (dolines and karren) only occur along the crests, appearing as the remains of a previous karst landscape. They formed before the fluvial erosion phase, and appear in the zones marked by the erosion which followed the ascending movements in the area. The surface stream network patterns and its density are closely related to the gneisses (Vavliakis et al., 1989) that overlaid the marbles until middle Miocene (Dinter, 1994b), indicating that surface flow was then driven by this impermeable cover during Miocene and progressively eroded it.

According to the data from drillings, the underground karst features develop at depth, quickly decreasing with depth (Dimadi, 1988). According to Marinos et al. (1987, 1994), the cross section of present day functioning kart conduits is approximately 10 times that of the conduits at depth.

The polje of Kato Nevrokopi (Fig. 1) is a typical karstic closed basin. Its catchment area representing the non-karstic part of the system extends over 441 km^2 up to 2200 m in elevation. It is composed of various geological formations, mainly alluvial deposits, granite—granodiorite massifs, gneiss and marbles. The surface stream network is interrupted by the marbles of the Falakro massif forming the Kato Nevrokopi basin. The main plain, located at the southwest of the town of Kato Nevrokopi, is a wide depression extending over 42 km^2 at an average altitude of 540 m. It is of tectonic origin and its formation began not earlier than the upper Pliocene (Vavliakis et al., 1989). The Quaternary filling is more than 300 m thick and consists of a repetitive alternation of breccia, conglomerates, sandstone,

silts, marls and clays. These formations constitute a multilayer aquifer particularly well developed in conglomerates (Leontiadis et al., 1983; Dimadi, 1988).

Hydrology

The mean annual rainfall during the period 1964–1983, on the north-western area of Drama varies from 600 mm in the plain to 1100 mm on the mountain. Nevertheless there is no direct relationship between the rainfall and the elevation, as usually observed in mountainous zones. In the study area the rainfall spatial distribution depends both on the altitude, the geographical position of the climatological station related to the relief, the well known ''screen effect'', and on the origin of the humid air masses (Dray et al., 1998; Villiers, 1990).

On its southern edge in the plain of Drama, the Falakro massif is drained by two main springs, Aggitis and Drama, with very close mean annual discharge over the period 1950–1960, respectively 5 and 6 $m^3 s^{-1}$ (Dimadi, 1988). The Drama spring (Fig. 1, w3) locates at 93 m in altitude in the Drama city downtown and corresponds to a line of springs appearing at the contact between the upper Pleistocene and the Holocene formations. Groundwater outlets are related to a fault system. Several sites have been drilled (Fig. 1, w4, w5, w6 and w7) in the marbles along the foot hills between the Aggitis and Drama springs. They show the existence of a groundwater flow from the Falakro massif towards the plain. The groundwater level in these wells is at the same altitude as the two springs.

In the western part of Falakro, the groundwater discharge is very limited, represented by Granitis, Ochiro and Panorama springs (Fig. 1, s6, s7 and s8). These springs are located at the contact with the granodioritic intrusions and their mean annual discharge is lower the 0.01 $m^3 s^{-1}$.

In the western part, the surface runoff into the Kato Nevrokopi basin is directed towards swallow holes, located close to the village of Ochiro, and sinks into the marbles. When the runoff flow exceeds the absorption capacity of the swallow holes, the water floods the plain creating marshes, sometimes a small lake. The piezometric map of the Kato Nevrokopi plain indicates groundwater flow paths also oriented towards the swallow holes.

Study methods and results

In order to characterise the framework in which the drainage structure develops and the functioning of the system, three study methods were applied:

1. The determination of the karstic drainage planes, according to the method proposed by Eraso (1985). That method aims to define the probable structure of the underground drainage network, or the karst network, based on the geometry of the microtectonic discontinuities of the marbles.
2. The characterization of the hydrodynamic functioning by analysing spring hydrographs using methods developed by Mangin (1975, 1984a,b).
3. The characterisation of underground flow conditions by means of the natural chemical tracers, according the approach proposed by Bakalowicz (1979, 1994).

Determination of the karstic drainage planes

Principle of the method

The relationship between karst conduits or some specific surface karst landforms (dolines, karrens), and the directions of tectonic discontinuities were noticed and studied for a long time. Two theories have to be considered. The first one assumes that karst features develop along all rock discontinuities, joints and bedding planes, in some way, according to their respective scales. The analysis of the whole distribution of the discontinuities could make it possible to determine the structure of the karstic conduits network (Drogue, 1974; Razack, 1978, 1980; Grillot, 1979; Rossier, 1985).

The second theory considers that rock discontinuities are used by groundwater flow for karst processes depending on their characteristics, aperture and fracture spacing, according to the direction of the regional hydraulic gradient. Only some of the rock open discontinuities are enlarged by karst processes. Consequently the relationship between discontinuities and karst conduits should exist only at the scale of the karst system (Eraso, 1985).

Most of the cave networks revealed by speleological explorations do not show obvious relations between their organization and the distribution of the whole opening planes, despite the fact that these networks result on the relationship between open joint planes and the hydraulic gradient at the moment of their development. However, the discontinuities within the carbonate rocks allow the groundwater flow and the development of the conduit network. The groundwater flows seem to ''choose'' some of the discontinuities which are then enlarged. Therefore in a systematic study, Eraso (1985, 1986) compared the directions of the karst conduits with those of the discontinuities, as well as their respective frequencies. It is based on the postulate, proposed by Arthaud and Choukroune (1972), and now accepted, that the groundwater flows exclusively use all the planes in distension, i.e. the open planes. The other planes of discontinuities would never be used by the groundwater flows.

The characteristics of these planes in distension can be determined by the microstructural analysis. If the ellipsoid of the deformations can be built from field analysis, the directions of these planes in distension may be defined: they contain the two main directions of stresses (major: $\sigma 1$, intermediate: $\sigma 2$) and they are perpendicular to the direction of the minor stress ($\sigma 3$). Eraso (1985) names them ''planes of drainage'', because they favour the groundwater flow. From a great number of analysed examples, he noticed that, systematically, the histograms of frequency distribution of the directions of the conduits, from cave maps, and the planes of drainage are similar at the massif scale.

Eraso (1986) also evaluates that, according to the relative position of both directions of the hydraulic gradient and of the drainage planes, the karst system should present different general shape and karst network. If the two directions are coincident, the karstic network is rather linear and the system develops in length. On the contrary if the two directions are perpendicular, the drainage network is more complex and the system more compact than in the case they are coincident. Consequently, the open discontinuities used by groundwater flows are enlarged by the karstic process

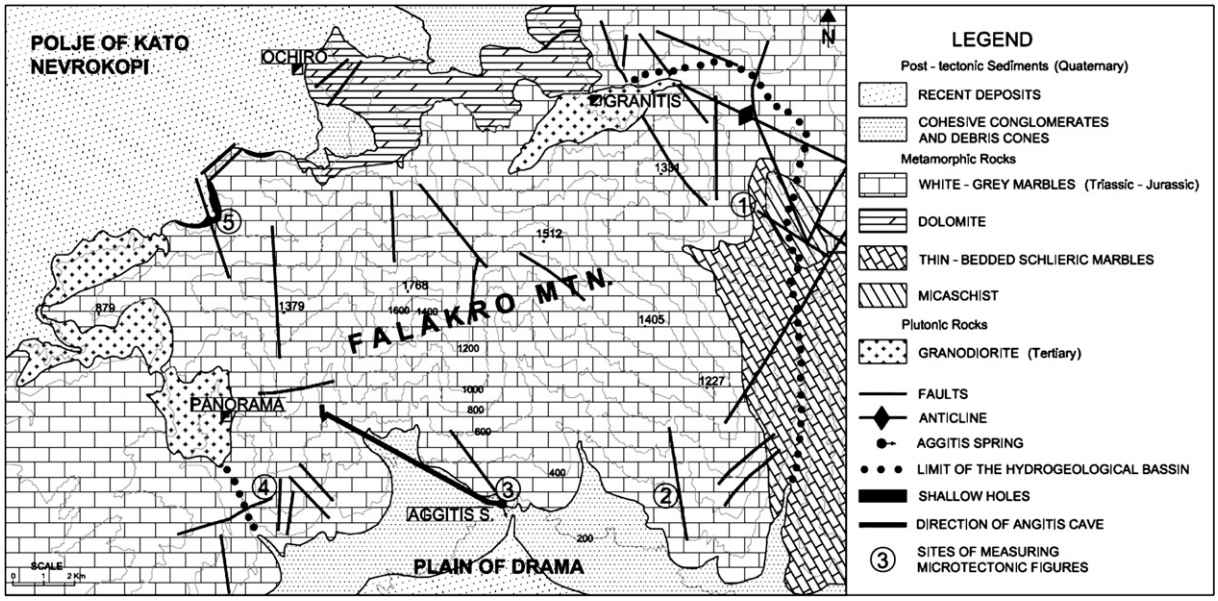

Figure 2 Location of the microstructural sites.

(dissolution) and organized in a network of conduits, depending on the degree of connection between the initial openings and on the orientation of the regional hydraulic gradient. In the case of the Falakro massif, the simple structural history of the marbles, dominated by the ascending movements of the Oligocene — Pliocene phase appears in simple and easily interpretable diagrams.

Results of microstructural measurements

The campaign of the entire microstructural measurements is related to the western part of mountain Falakro. The selected sites are mainly in the grey marbles at the base of the marbles and are related to five sectors (Fig. 2). A total of 326 measurements were obtained. The tectoglyphes, i.e. the microtectonics features, are the following: conjugated faults, calcite veins and striated faults. The software ERASO v.4.0 (1998) was used for the computation.

For each site and for every measure, the microstructural analysis of the tectoglyphes helped in determining the ellipsoid of deformations and the corresponding extension plane, i.e. the drainage plane. The histogram of distribution of these planes according to their direction represents their distribution law (Fig. 3). The comparison of this histogram with the representation of the poles of the drainage planes on a Schmidt diagram (Fig. 4) makes it possible to distinguish the three main families of drainage planes, and a fourth which is less significant and only observed at the sectors 1 and 3.

(1) 135—145°N with a large dispersion and a 85°SW dip. This is the principal direction.
(2) 55°N with a dispersion of 10° and a 85°SE dip,
(3) 10—15°N with a 78°SE dip.
(4) 100°N with an almost vertical dip.

Only a unique karstic conduit was identified in the Falakro massif. It originates and develops from the Ochiro shallow holes, at the north-west, towards Aggitis cave at the south. It was explored on 8555 m starting from the Aggitis spring. This conduit is subdivided in several branches with variable directions and lengths. The distribution of cumulated probabilities of the drainage planes, i.e. the prediction, which represents the theoretical function of

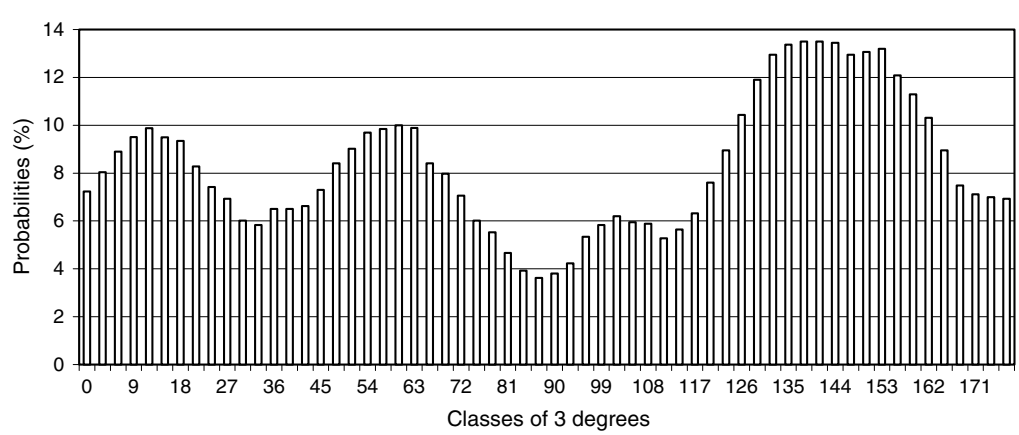

Figure 3 Distribution law of the extension planes.

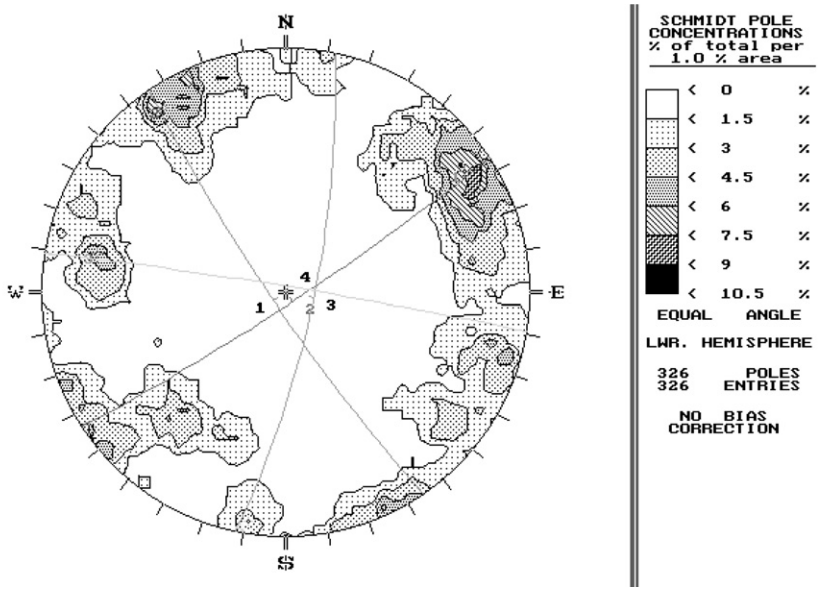

Figure 4 Schmidt diagram (drainage planes).

Table 1 Microstructural measurements

Classes (°)	Ranges (°)	Conduits			Prediction			K.S. error
		Length in m	%	% Cumulated	Planes	%	% Cumulated	
1	0–15	413	4.828	4.828	27	8.282	8.828	0.997
2	15–30	680	7.943	12.772	32	9.816	18.098	1.538
3	30–45	280	3.271	16.042	17	5.215	23.313	2.099
4	45–60	839	9.812	25.855	28	8.589	31.902	1.746
5	60–75	666	7.788	33.642	32	9.816	41.718	2.331
6	75–90	466	5.451	39.094	15	4.601	46.319	2.086
7	90–105	1380	16.132	55.225	18	5.521	51.840	0.977
8	105–120	386	4.517	59.742	14	4.294	56.135	1.041
9	120–135	1392	16.272	76.014	35	10.736	66.871	2.639
10	135–150	493	5.763	81.777	42	12.883	79.755	0.584
11	150–165	1186	13.862	95.639	44	13.497	93.252	0.689
12	165–180	373	4.361	100.000	22	6.748	100.000	0.000

Calculation of the percentage error Kolmogorov–Smirnov test.

Maximal error: $\sum \max \leqslant \frac{\left|\sum \text{con} - \sum \text{pre}\right|}{\sqrt{\text{no of classes}}} \leqslant 2.331$.

Statistical certainty: $100 - \sum \max \geqslant 100 - 2.331 = 97.669\%$.

probability distribution (Fig. 3), is compared to the distribution of the cumulated probabilities of the observations, the conduits, by using the Kolmogorov–Smirnov test. This test makes it possible to validate the degree of success of the distribution law of the theoretical function chosen as being representative of the data, i.e the drainage planes. This statistical test calculates for the same class, the difference between theoretical and observed probabilities, i.e. the conduits. The results (Table 1) show that the distribution law of the drainage planes obtained for the western part (sector) of Falakro is acceptable.

This result can be explained by the structural context. The extensional deformation dominates from Miocene to present, with the minor principal stress axis ($\sigma 3$) oriented NE–SW during late Miocene–Pliocene, and N–S, the mean direction in northern Greece, since the limit Pliocene – Pleistocene until today. Moreover, all the fractures are parallel to the ante-Miocene ductile structures (Chagipanagis et al., 2000; Dinter, 1994b; Doutsos and Ferentinos, 1984). The most frequent extension planes are oriented NW–SE, identical to the regional direction of the hydraulic gradient in the western part of the studied area. This corresponds to the direction of the development of the main conduit Ochiro–Aggitis, which should facilitate a rapid transport of groundwater. In the eastern part, the hydraulic gradient is oriented NE–SW that coincides only with the direction of a weak number of drainage planes. Consequently, in this area the groundwater flow towards Aggitis spring cannot as easy as in the western part so that the karst network does not drain so efficiently this area.

Functioning of the karst system

The spring hydrograph analysis

The hydraulic behaviour of the Aggitis karst system was studied by means of several methods for analysing the spring hydrographs, proposed by Mangin (1975, 1981a,b, 1984b) and Marsaud (1997). The distribution of the sorted discharge values, from an annual hydrograph, provides information on the mechanisms that are able to modify the distribution law of discharge values, i.e. to influence the mode of the flows, such as the existence of overflow springs, or the extra input or output of water coming from or towards a neighbouring system.

The recession curves of spring hydrographs inform on the infiltration mode and on the characteristics and the importance of the saturated zone. Soulios (1985, 1991) applied the method on karst springs of Greece.

The spring hydrograph was also analysed at a scale longer than one hydrological year, allowing a better approach of the transfer function of the system that is the response to the precipitations. The flow time series is studied, alone or by a cross analysis with the rainfall time series, by using the correlation and spectral analysis (Max, 1980; Box et al., 1994). The time series analysis is a systemic approach of the karst behaviour, examining the input—output relations by means of statistical functions. The aquifer works as a filter transforming the input signal into the output signal, the degree and the nature of this transformation being related to the characteristics of the flows in the aquifer (Mangin, 1981a,b, 1984b; Bouchaou et al., 1996; Larocque et al., 1998; Morales-Juberias et al., 1996; Padilla and Pulido-Bosch, 1995; Marsaud, 1997).

The simple correlation analysis, applied to the discharge time series, i.e. the Aggitis spring hydrograph, provides a correlogram, or an autocorrelation function of the time series with increasing time steps. The shape of the curve, representing the successive values of the autocorrelation coefficient, points out the interdependence of the events, and thus it gives information about the memory effect of the karst system. The comparison of the output and input signals produces the cross-correlogram function representing the impulse response of the system, i.e. the unit hydrograph, on condition that the input function is random.

The discharge time series can be also analysed in the frequency mode, i.e. according to t^{-1}. Therefore the density of the spectrum variance corresponds to Fourier's transform of the correlogram. The simple and cross spectral analyses complete the study of the correlogram functions providing information, particularly on the regulation time of the system, i.e. its inertia related to the nature of its storage, and on the frequency of the phenomena that produce the variations of flow at the spring.

Results of the spring hydrograph analysis

The hydrodynamic analysis is based on the daily discharge flow recorded at the Aggitis spring, during two hydrological years from 01/10/1984 to 30/09/1986, i.e. a total number of 730 days. The rainfall data are those from the meteorological stations of Granitis at 790 m altitude and Ochiro at 550 m altitude for the same period.

The monthly variation of rainfall at Granitis and Ochiro (Fig. 5) are similar. However, Granitis rain gauge generally records rainfalls higher than Ochiro because of its higher altitude and its different exposition to the atmospheric disturbances coming from the south. The location of Ochiro station is like in a shelter in the alluvial plain at north of Falakro mountain. Unfortunately no climatological station exists above 840 m altitude to give more information on rainfall space distribution.

During the study period (1984—1986), the discharge time series of Aggitis spring presents significant differences, between the first (1984—1985) and the second (1985—1986) hydrological year. The differences appear in their mean annual discharge (respectively 2.64 and 6.12 $m^3 s^{-1}$), their variability index (Q_{max}/Q_{min} with monthly extreme data) respectively 11.3 $m^3 s^{-1}$ (Q_{min} = 0.56 $m^3 s^{-1}$, Q_{max} = 6.31 $m^3 s^{-1}$) and 31.3 $m^3 s^{-1}$ (Q_{min} = 0.80 $m^3 s^{-1}$, Q_{max} = 25.01 $m^3 s^{-1}$) as well as their seasonal variations (Fig. 5).These differences obviously are related to the differences in rainfall distribution of the two considered hydrologic years (Fig. 5). The annual rainfall corresponding at Granitis station for the first year is 781 mm and the second 1195 mm and at Ochiro station respectively 546 mm and 855 mm.This shows that the karst system is very sensitive to the change in the rainfall regime. The mean annual flow increased by 2.30 times while rainfall increases by 1.80—2.00 on the western and the northern parts of the drainage area of Kato Nevrokopi and by 1.20—1.70 on the plains of Kato Nevrokopi and Drama, as well as on the area of Falakro mountain.

During floods, spring hydrograph shows a sudden increase in discharge followed by a relatively slow recession after the end of rainfall (Fig. 5). For instance, the flow changed from 0.73 $m^3 s^{-1}$ (24/11/1985) to 12.54 $m^3 s^{-1}$ (26/11/1985) and then to 4.19 $m^3 s^{-1}$ (7/12/1985). The lag time between the rainfall event and the flow rate increasing is a few hours. It depends on the season, from less than 15 h from November to June when the swallow holes function, up to 30 h from July to October. The functioning of the swallow wholes tend to reduce the lag time. The shape of the hydrograph allows assuming that the underground flow is driven by a main conduit system from Ochiro to Aggitis. This well developed conduit system favours the input mass flux to rapidly reach the output, i.e. the Aggitis cave.

The sorted discharge distribution is analysed for each of the two studied hydrologic years (1984—1986) separately and both show a change in their slope around the 22.00 $m^3 s^{-1}$ indicating a change in probability of the high flow rate occurrence becoming smaller than the predicted by the normal distribution at lower flow rates. This change is explained by a seasonal overflow spring located a few meters above the main spring, overflowing when the main spring flow is 22.00 $m^3 s^{-1}$ or more; its flow is not controlled by the discharge gauging station.

The flood events considered for the recession analysis are those beginning on 27/5/1985 and on 16/6/1986. Both floods are the last of the hydrological year and provide recession without any individual storm pulse due to the absence of summer rains. The two recessions (Fig. 5) have comparable characteristics: (i) a long duration of infiltration, respectively 82 and 96 days, (ii) peak flow discharge (Q_0) respectively 5.33 $m^3 s^{-1}$ and 8.11 $m^3 s^{-1}$, discharge at the beginning of the low stage (Q_{r_0}) respectively 1.27 $m^3 s^{-1}$

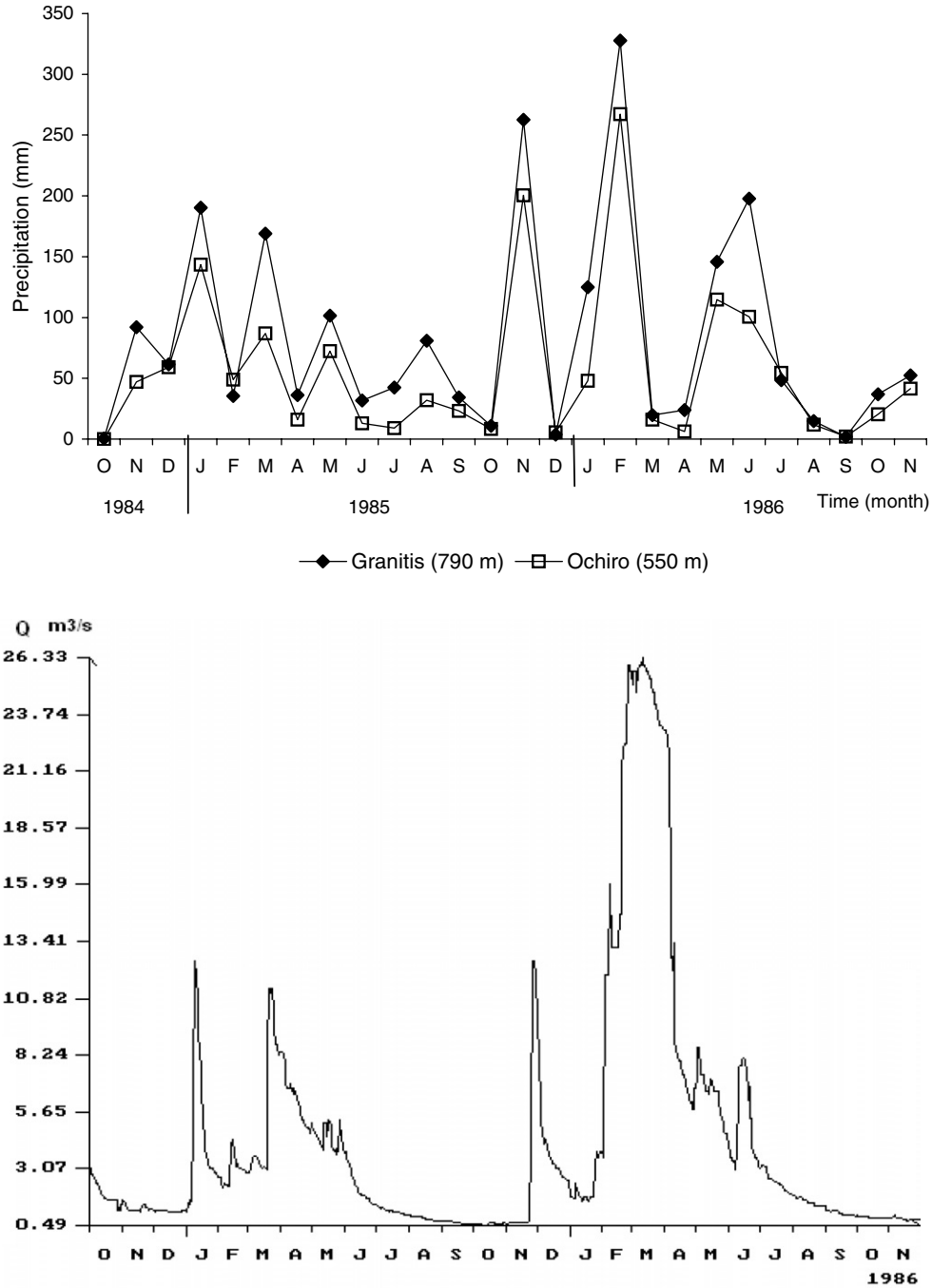

Figure 5 Time series of rainfall at the Granitis and Ochiro station and discharge of the Aggitis spring, from October 1984 to November 1986.

and 1.29 $m^3 s^{-1}$, infiltration discharge at the beginning of the recession (q_0) respectively 4.06 $m^3 s^{-1}$ and 6.83 $m^3 s^{-1}$, (iii) infiltration volumes in the same range, respectively 4.30 and 11.00×10^6 m^3, and (iv) an important dynamic volume, respectively 18.50 and 35.30×10^6 m^3. The values of the heterogeneity coefficient ε, respectively 0.144 and 0.082, indicate a dominant slow infiltration. The Maillet's coefficient α, with relatively low values, 3.10 and 5.90×10^{-3}, indicates that the phreatic zone is relatively easily drained out by karst conduits. However, the two recessions correspond to different recharge conditions: the lake drained by swallow holes did not exist during the first year because of a low rainfall. Moreover, the hydrological events preceding the recessions are different: the second recession takes place after a very high flood that exceeded 26.00 $m^3 s^{-1}$. The volume of water stored during the second recession in the lake and in the karst phreatic zone, as well as in the alluvium aquifer of the Kato Nevrokopi polje, was much greater than that before the first recession.

Correlation and spectrum analyses

The discharge time series, constituted by the data of the two successive hydrologic cycles, were analysed. The obser-

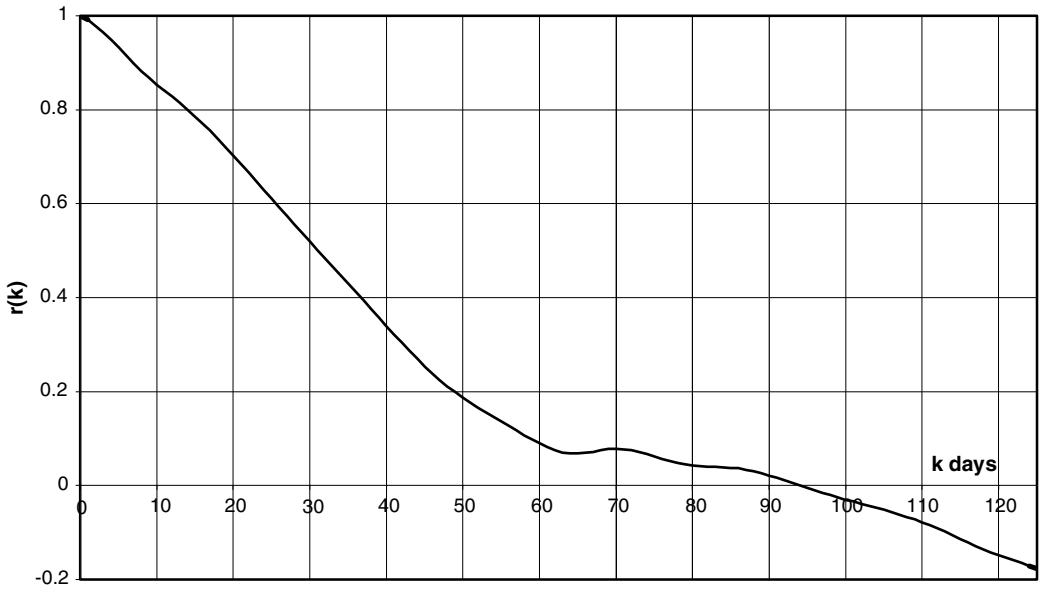

Figure 6 Simple correlation function of the 1985—1986 discharge time series of the Aggitis spring.

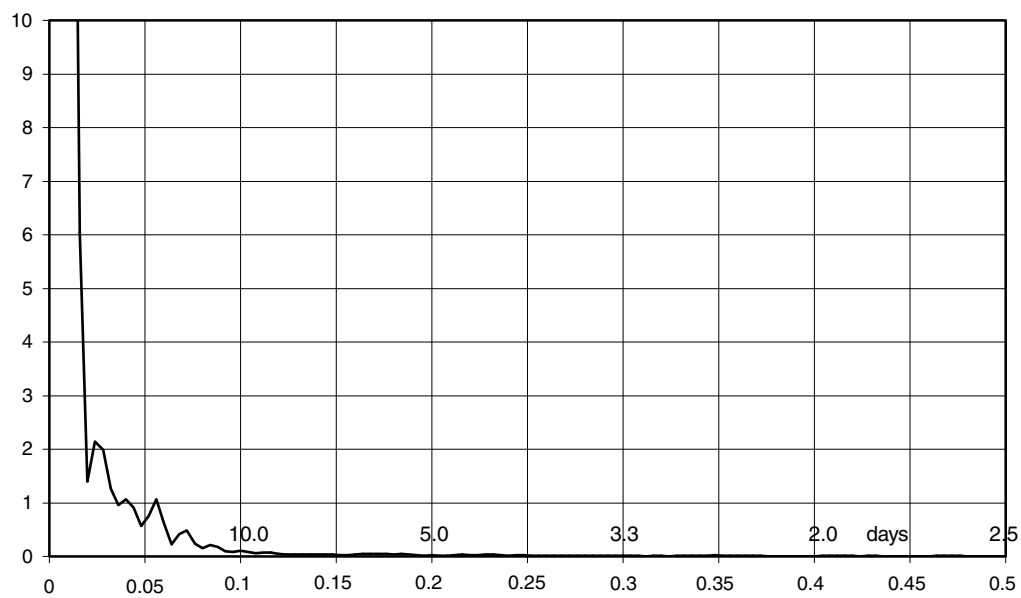

Figure 7 Spectrum function of the 1985—1986 discharge time series of the Aggitis spring.

vation window is limited to 125 days. The simple correlation function shows that the system has a significant memory effect, about 50 days (Fig. 6). The spectrum function (Fig. 7) shows that the time series characterises a system with a low truncation frequency, filtering all the events with a frequency higher than 0.6, i.e. a duration approximately lower than 15 days.

The cross-correlation function gives a good representation of the impulse response of the system, because the input signal, the precipitations time series, is purely random as shown by its correlation and spectrum functions. This impulse response is very complex and long (Fig. 8).The regulation time, given by the duration of the impulse response, is very long, more than 125 days. The low values of the function characterize a poor dependence with the input time series. This long-term effect, approximately 3—4 months, could be related to the snow melting, which is not taken into account in the precipitation time series, and which cannot be approximated in any way. The amplitude function confirms that the system filters well all the signals with duration shorter than 15 days and only the seasonal signals are transmitted.

The analysis of natural tracing

Principles and method

The physical and chemical characteristics of the karst groundwater and their variations during the hydrological year partly depend on the geologic environment. These characteristics are mainly ruled by the groundwater flow conditions, flow velocity, residence time, confine or unconfined

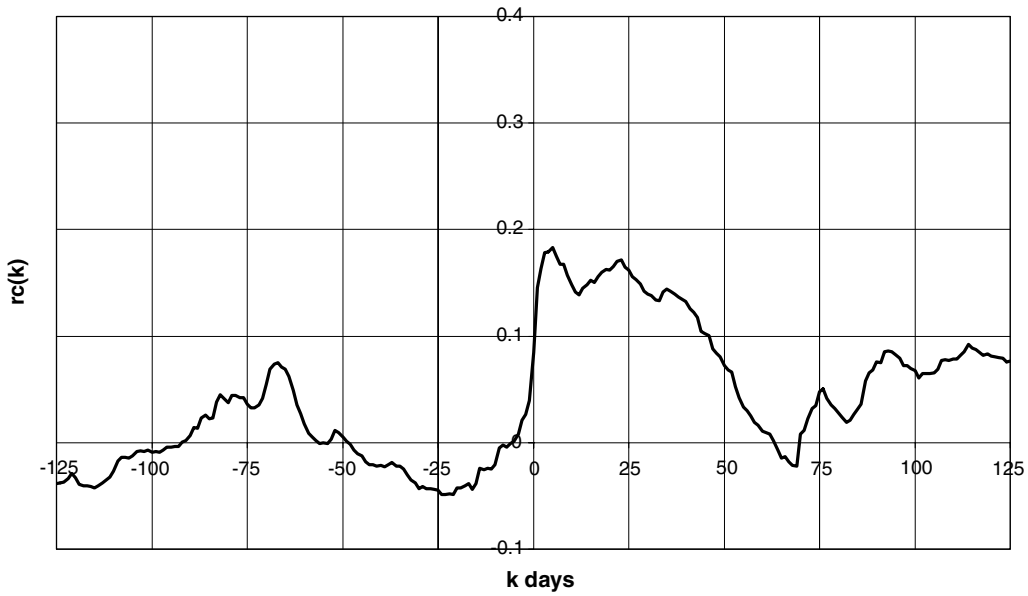

Figure 8 Cross-correlation function between the rainfall at Ochiro and the discharge of the Aggitis spring (1985—1986 time series).

flow in conduits, depending on the importance of the development of karst features, controlling the distribution of slow and quick flow in the infiltration zone as well as in the phreatic zone (Bakalowicz, 1979). Consequently groundwater geochemistry is a resource of essential knowledge that makes possible the reinforcement of the more traditional hydrodynamic approach.

The study related to the physical parameters, electric conductivity, pH, temperature, and to the dissolved inorganic ion contents (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, HCO_3^{-}, NO_3^{-}). In karst aquifers the state of the $H_2O - CO_2 -$ carbonate chemical system depends on the flow conditions (Bakalowicz, 1979; Bakalowicz, 1994); consequently the fundamental parameters of the system, the CO_2 partial pressure, pCO_2, and the saturation index for calcite, ISc, and dolomite, ISd, as well as the Mg/Ca ratio were calculated and considered as the main variables.

The concentrated recharge from the Kato Nevrokopi catchment area was sampled at the w2 well (Fig. 1). The discharge zone along the contact between Falakro Mountain and the alluvial plain of Drama was sampled at the following points: springs Aggitis and Drama, and wells w4, w5, w6 and w7, as well as Kefalari spring (s12) another significant spring in this region. As the Drama spring discharges in the city, sampling was done in an artesian well (w3) located near the spring. Groundwater discharge in the western part of Falakro was studied by the sampling at s6 and s7 springs (Fig. 1).

The whole set of sampling points was monthly surveyed during the hydrological year from November 1996 to October 1997. Only some samples could be collected from the concentrated recharge at Ochiro swallow holes, which is intermittent, because of storage and irrigation.

Finally, this chemical data time series was complemented by a specific sampling campaign related to some springs and wells of the Kato Nevrokopi area. The springs (s1, s2, s3, s4, s5, s8, s9, s10, s11 and r1, see Fig. 1) were selected according to their altitude, between 670 and 1200 m altitude and to the dominant lithology, granite, schist—gneiss, marble, of their recharge area. The point r1 corresponds to a small stream from springs discharging along a line. The w1 and w8 wells are located in the alluvial formations of two small plains related to that of Kato Nevrokopi.

Overall geochemical characteristics

Groundwaters discharging from Falakro Mountain (Aggitis, w3, w4, w5, w6, w7, s6 and s7) are of calcium bicarbonate type (Table 2). At Aggitis spring and wells, the calcium content represents 78—82% of the total cation content, and the bicarbonate content 88—94% of the anion content. Water from s6 and s7 springs discharging at the contact of limestones with the granodiorites are characterised by low calcium and bicarbonates contents, approximately 70—75%, associated to an increase in sodium and sulphate contents.

Among all these groundwaters, Aggitis spring shows particular characteristics: it is the coldest water (12 °C) compared to the wells (16 °C) and the lowest mineralised with an electric conductivity in the range 300—400 $\mu S\ cm^{-1}$ to be compared with that of the other sampling points (400—600 $\mu S\ cm^{-1}$). Its pCO_2 is obviously lower and much more variable than groundwater in wells, in the range 0.25—1.12×10^{-2} atm. The calcite saturation index SIc shows that all the waters are supersaturated, except some samples of the Aggitis which are undersaturated as a result of fast flow in the open karstic channels. The supersaturation is due to degassing in the Aggitis underground river, quite open to the atmosphere. The supersaturation of the wells water could result from the absence of pumping at the time of the sampling; pumping for a long time would have provided water samples without any chemical evolution. However these data show that groundwater from zones badly connected to conduits presents pCO_2 in the same range as most groundwater in the Mediterranean regions.

The sulphate concentrations are in the range 17—20 $mg\ L^{-1}$. They are higher in wells w6 and w7 than in all others can be related to the location of these two wells close to Aggitis spring, and to their high mineralization.

Table 2 Summary of the water chemical data

Sampling sites	Sampling date	Number of samples	Site Symbol	T (°C)	EC (μS cm^{-1})	ISc	pCO_2 (10^{-2} atm.)	Ca (mg L^{-1})	Mg (mg L^{-1})	Na + K (mg L^{-1})	Cl (mg L^{-1})	SO_4 (mg L^{-1})	HCO_3 (mg L^{-1})	NO_3 (mg L^{-1})
Agitis sp.	Mean	14	AG	12.1	342	0.11	0.36	59.2	6.5	3.5	2.4	15.0	199.1	3.8
Drama artesian well	Mean	14	DRw3	15.5	433	0.22	0.70	75.4	9.5	3.0	3.6	8.9	263.7	6.7
Prosotsani IGME well	Mean	13	w6	17.1	542	0.25	1.08	89.1	13.6	2.9	4.5	19.2	313.1	9.6
Kokkinogia B well	Mean	11	w7	14.9	532	0.41	0.79	95.5	11.2	2.2	2.9	17.3	325.3	7.1
Drama well G1	Mean	14	w5	15.9	445	0.38	0.48	75.3	9.4	2.4	3.4	6.1	264.1	4.6
Granitis sp.	Mean	14	s6	11.7	206	−1.17	0.49	23.7	4.2	6.8	3.4	16.7	79.0	8.7
Ochiro fountain	Mean	8	s7	11.7	266	0.22	0.10	40.1	4.2	6.2	3.0	16.9	139.8	0.3
Kefalari sp.	Mean	13	s12	16.6	426	0.20	0.69	68.2	12.5	4.5	4.6	4.1	264.2	5.1
Monastiraki well	Mean	13	w4	15.9	444	0.22	0.63	71.3	9.5	3.0	3.4	5.5	253.3	6.2
Ochiro well	Mean	3	w2	11.9	526	0.21	0.70	71.8	20.3	6.0	4.8	19.0	299.0	12.5
Profitis Ilias	16/10/97	1	s9	11.6	314	−0.04	0.56	67.4	2.6	3.2	1.6	0.5	215.2	0.4
K. Vrondu 2	15/10/97	1	s5	10.9	171	−0.40	0.15	25.2	5.6	6.6	2.1	12.0	104.9	1.3
K. Vrondu 1	15/10/97	1	s4	10.8	147	−0.43	0.10	20.4	5.1	5.3	2.1	8.0	92.7	0.4
Lefkogia S.	17/10/97	1	s10	12.9	473	0.21	1.07	82.6	13.2	12.5	4.1	0.5	334.3	2.6
K. Vrondu 3	15/10/97	1	s8	9.6	325	0.40	0.25	71.4	2.8	1.7	1.7	8.0	223.3	0.4
Lefkogia PA well	17/10/97	1	w1	12.0	397	−0.24	0.99	46.6	18.1	18.9	6.3	23.0	256.2	0.0
Exochi S	15/10/97	1	s11	12.1	418	0.32	0.49	69.4	14.2	7.4	3.0	17.0	284.3	5.3
Akrino well	16/10/97	1	w8	12.0	423	0.36	0.46	84.6	5.9	3.9	1.8	2.0	257.4	19.8
Lefkogia Pot. River	17/10/97	1	r1	8.6	496	0.68	0.31	78.0	21.4	12.0	4.8	0.5	356.2	0.9
Periphori 1	17/10/97	1	s2	8.1	69	−1.52	0.09	8.3	1.1	5.8	2.0	0.5	38.3	2.6
Periphori 2	17/10/97	1	s3	9.5	74	−1.31	0.08	9.4	0.6	6.7	2.7	0.5	43.2	0.9
Krioneri	16/10/97	1	s1	7.2	60	−1.63	0.10	7.8	1.1	4.2	1.4	0.5	36.6	0.4

N indicates the number of samples collected from November 1996 to October 1997.

Regional sampling (October 1997)

The regional sampling carried out on the springs and wells in October 1997, provided a complete set of hydrogeochemical data (Table 2) in order to define the main characteristics of the underground flows. Rather than a detailed description of the data by means of statistical parameters and two-variable correlations, we preferred to apply the principal components analysis (PCA). This method indeed allows taking in account at the same time the regional variations of all the considered chemical variables and their interrelationships (Bakalowicz, 1994). This is a powerful method of description and classification of data helping to their interpretation. The present analysis is mainly based on the experience gained in studying the hydrogeology of karst systems.

The PCA results are synthesized by considering the data separately in the variable and sample spaces. Factors are defined from deciphering the total variance of the set of data. Principal planes are represented by taking the factors two by two. Therefore, the variables are represented in the principal planes according to their correlation with the factors. Those which are close to the circle of correlation, which radius $r = 1$, play a determining role in the significance of the factor axes, whereas those close to the centre do not play any role. In the same way, the samples are projected on the principal factor planes, successively taken two by two. Their relative position and their distribution can be interpreted according to the axes on which they are dependent. The significance of the factor axes is provided by interpreting the relationships between variables, samples and factors, taking into account their geochemical significance.

The variables considered in the analysis are as follows: temperature T, electric conductivity EC, calcite saturation index SIc, CO_2 partial pressure pCO_2, the total concentration in Ca, Mg, Na + K, HCO_3, Cl, SO_4 and NO_3. The PCA makes it possible to characterize and to compare the water of Aggitis spring to all those of the area (Fig. 9). In the var-

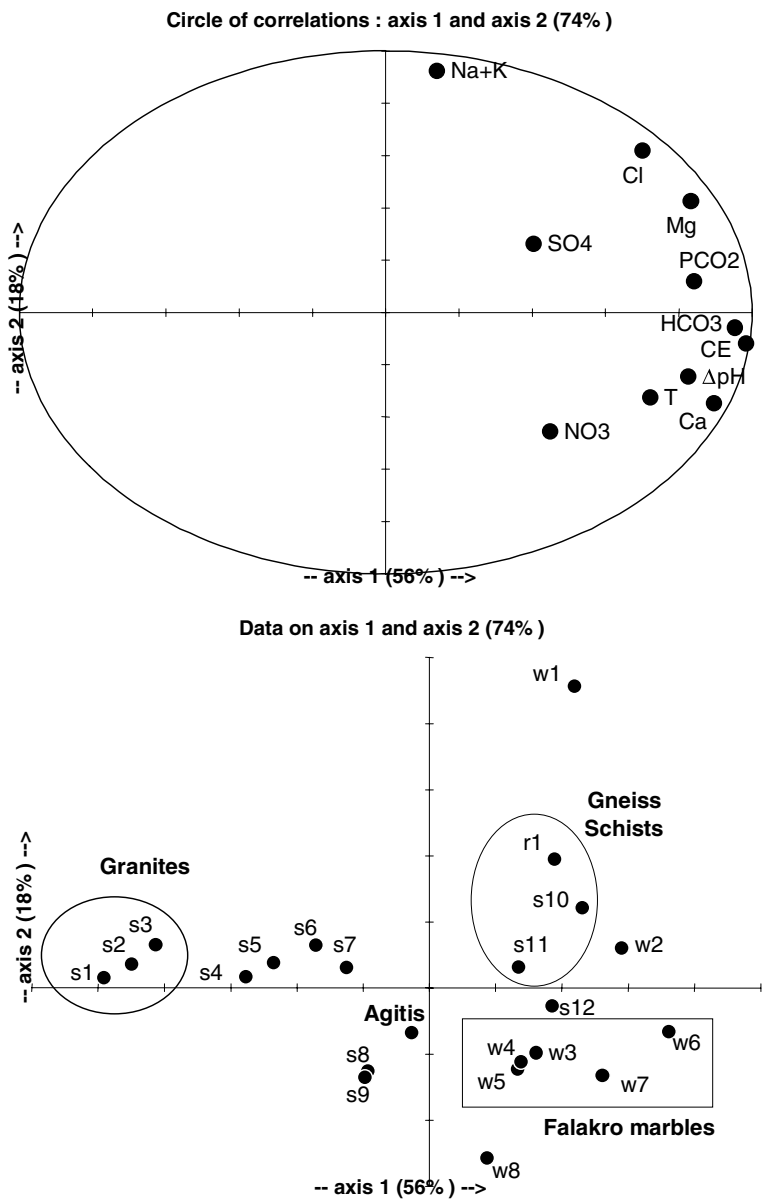

Figure 9 Principal component analysis of all water geochemical data collected during October 1997.

iable space, the first three axes explain 84% of the total variance. The first axis F1, explaining 56% of the total variance, is determined by EC, Ca and HCO_3 and at a lower degree by SIc, pCO_2 and Mg; thus the F1 axis accounts for the H_2O—CO_2—carbonate chemical system. The F2 axis, explaining 18% of the total variance, is defined by alkaline ions Na + K and partly by Cl, also carried by F1. Finally, the F3 axis with 10% of the variance is only determined by SO_4.

Despite their low concentration (<25 mg L^{-1}), the sulphate contents make it possible to differentiate the waters between them. However, the independence of sulphate from all the other chemical variables, expressed by F3 factor, locates their origin to a source of sulphur dispersed in the massif. The aforementioned source should be the sulphide minerals (copper, lead, zinc and iron) known in the marbles and at their contact with the schists or the gneisses, generally trapped in paleokarstic structures with the manganese oxides. Thus the oxidation of these sulphur minerals contributes to the chemical content of groundwater at a low concentration level and much localised.

In the sample space, factor F1 opposes groundwater from the marbles (wells w6 and w7) to those from the granite-type rocks (s1, s2, s3, s4 and s5), whereas factor F2 opposes groundwater from schists and gneiss (w1, r1, s10, s11) to those from marbles. All the other waters seem to be a mixture between these three water types, with regards to their concentration related to carbonate and Na, K and Cl. Thus the F1—F2 plane, which explains 74% of the total variance, makes it possible to distinguish these three basic groups of groundwater:

- those from the granites, s1, s2 and s3, at the negative extremity of F1, i.e. without carbonates and with low value of SIc, obviously undersaturated with respect to calcite;
- those from the schist and the gneiss, r1, s10 and s11, enriched in Na and K;
- those from the marbles, w3, w4, w5, w6 and w7, characterised by high concentrations in Ca, Mg, HCO_3 and high pCO_2 and SIc.

The Drama spring, w3, clearly belongs to the group of waters from the marbles. Aggitis spring is located close to the gravity centre, which means that it is characterized by the three types of groundwater that constitute its origins. This shows the complexity of the recharge of the Aggitis karst system, originating at the same time from Falakro Mountain and from the Kato Nevrokopi catchment area. In this last component, the contribution of the surface drainage network dominates: according to the tritium contents, low in the groundwater of the alluvial aquifer around Ochiro, and high in the Aggitis karst spring (Leontiadis et al., 1983) so the recharge of the karst aquifer from the alluvial aquifer is very limited.

Time variation of water chemistry

Whereas the chemical composition of the water wells is relatively stable during the hydrologic year, this of the Aggitis spring is highly variable. The sulphate concentrations illustrate well this variability (Fig. 10). During winter and spring, the season of recharge by water from the Kato Nevrokopi basin, through the Ochiro swallow holes, sulphate contents vary between 15 and 20 mg L^{-1}, while they are as low as 5—10 mg L^{-1}, i.e. those of the wells the most distant from Aggitis, w3, w4 and w5, during the low flow stage, when the swallow holes do not function.

Discussion and conclusion

It is only since Pliocene that the Falakro carbonate massif is subjected to the processes of continental erosion and more particularly to karstification. This recent history presents the development of a karst with a very variable intensity in the different sectors, at its surface as well as in depth. Thus the Aggitis spring is the discharge point of a karst system characterised by a well developed karst network, whereas the Drama spring is the discharge point of a poorly karstified system.

The Aggitis karstic network obviously developed from the Kato Nevrokopi basin, through Falakro Mountain, which forms a natural barrier to the surface flows gathered in this closed depression, or polje. In the carbonate massif, the direction of the planes of fractures in distension, which are the most favourable to the groundwater flows, coincides with the direction of the potential hydraulic gradient between the Kato Nevrokopi polje and the regional base level formed by the quaternary plain of Drama. This supported the development of a karstic drainage network preferentially towards Aggitis, rather than towards Drama. Due to this fact, the karst network mainly represented by Mara cave whose entrance is the Aggitis spring, obviously developed starting from the basin of Kato Nevrokopi and crossing the Falakro massif, which forms a natural barrier to the surface flows gathered in this closed depression.

Contrary to most cave systems, the Mara cave network does not show a multiphase evolution, with a multi-storey development related to variations of the base level, which were eustatic as well as tectonic. This is an evidence for a rapid and easy development of karst drainage from the polje to Aggitis spring, while during the same time in the absence of concentrated recharge, the karst network poorly developed towards the Drama spring. From geology and hydrogeology settings, the Aggitis karst system should be considered as more complex and achieved than the Drama system.

From the hydrodynamical analysis, the functioning of the Aggitis spring appears complex because certain characteristics are not really karstic. First of all, the infiltration occurs for a long time, between 80 and 100 days; the occurrence of snow at high elevations could be the cause of this duration. But the recharge is also dominated by a slow or delayed infiltration, imposed by the surface flow part of the system, forming the catchment area the polje. The phreatic zone in the karst aquifer is relatively well drained, as shown by the recession coefficient α in the range 0.003—0.006, however characterised by a very large dynamic storage, 18—35×10^6 m^3, responsible for the large memory effect of the system, up to 50 days. The impulse response of the system, very complex, characterizes rather a system with a not really karstic functioning. However, the results of the cross-correlation analysis are marked by uncertainty, because the input function considered the rain and not the result of the snow cover melting, which is the effective input function.

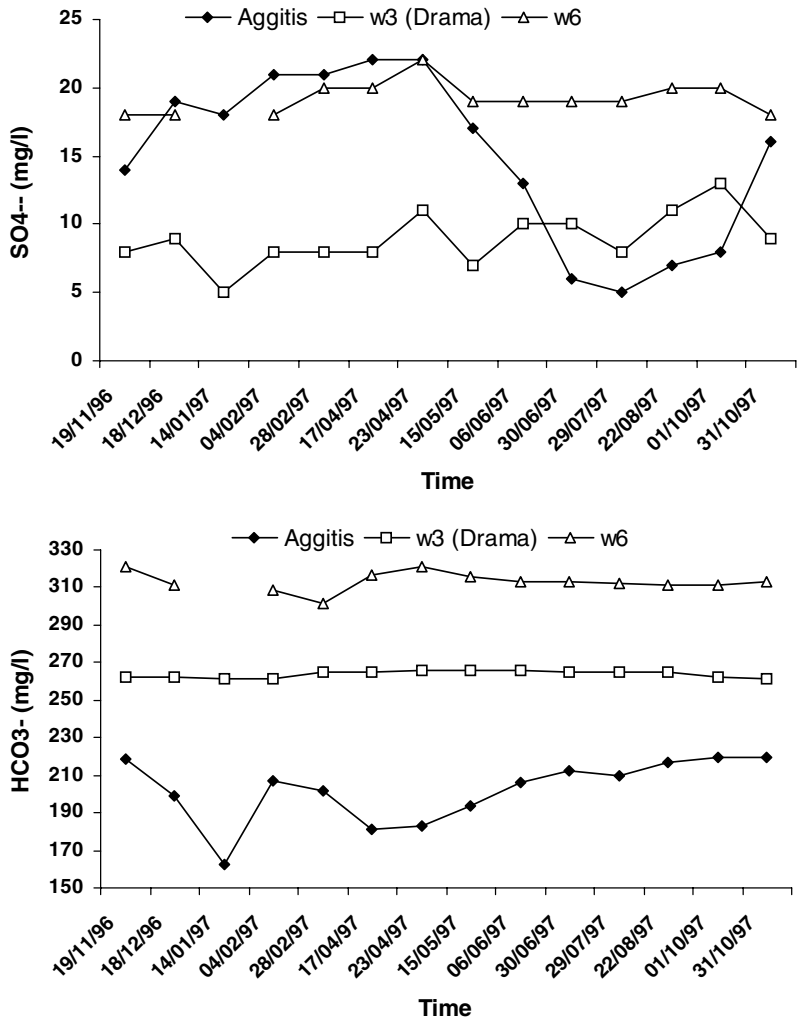

Figure 10 Seasonal variations of sulfate and bicarbonate contents in water of the Drama and Aggitis springs and in w6 well.

The study of the natural tracing by means of the water geochemistry shows that the recharge of the Aggitis karst system is complex in comparison with Drama system. The Aggitis groundwater is cold and weakly mineralised, with relatively high seasonal variations, what shows that groundwater flows relatively rapidly for a significant part. The Aggitis karst system has a functional karst network, easily draining a part of the recharge through a part of the system. The other part of the system discharging at the contact of the Drama plain does not present any typical karst behaviour. The recharge of the Aggitis karst aquifer is much diversified. It is formed by a significant runoff from the Kato Nevrokopi basin, by the drainage of the Ochiro seasonal lake and by the direct infiltration in the karst massif. The recharge of the karst aquifer by groundwater from the alluvial aquifer of the Kato Nevrokopi plain should be considered whenever it is not very important or variable during the hydrologic year.

These contradictory characters can be partly due to the role of the multi-layer aquifer in the alluvial filling of the Kato Nevrokopi polje acting as a filter. The temporary lake occupying the polje also plays a comparable part. However during the recession, the geochemical characteristics of the groundwater obviously show that a considerable storage is located in the marbles. That means that the karst is sufficiently developed in the marbles for having created the conditions for groundwater storage, but not sufficiently to facilitate their easy drainage towards the spring. All the data show that the Aggitis karst system can offer very interesting conditions for an active management of its groundwater, and especially its efficient seasonal recharge.

Contrarily the part of the massif Falakro drained by the Drama spring does not present any really karstic characteristics, as well in its landforms as in its hydrological functioning. The non-carbonate formations, schists and gneiss, are not drained by the carbonate massif and the Drama spring presents flows poorly variable in quantity and chemistry.

These differences in karst development noted between the two systems of Drama and Aggitis are expressed by the pCO_2 of their groundwater and by their dissolved carbonate concentrations, as well in the springs and in the wells. Indeed, the pCO_2 is definitely lower and much more variable in the waters of Aggitis spring than in those of the wells and the Drama spring. This difference results in the existence of the karstic conduits that allows an aeration of groundwater and consequently the partial degassing of

the dissolved CO_2. This produces a difference in their chemical composition, the water of Aggitis spring having a lower mineralization than Drama. The water of Drama, richer in dissolved CO_2 and in carbonates, degasses at the spring and abundantly precipitates travertines.

However, the data on the Drama spring is not sufficient to push the interpretation further. The current overexploitation of the Drama carbonate aquifer is causing the drying up of the source and the generalized fall of piezometric surface. These conditions do not make it possible to further complete the study of this aquifer in its natural functioning despite the fact that the springs may flow again after rainy years recharging the aquifer.

Thus, in the same area, under the same climate, in the same geological formations and during the same geological time, i.e. since middle Pliocene, the karst features developed very differently in the carbonate massif, according to the existence or not of concentrated recharge from surface flows of a non-karstic area. The example of the Aggitis karst system shows that the localized inputs of the surface flows into a carbonate massif, allows the fast installation of a karstic network starting from the entry points, the swallow holes, favouring by this supplementary offer of water flow. In the case of the western part of Falakro massif, this organization of the underground drainage network was facilitated by the fact that the general direction of flow, imposed by the hydraulic gradient between the swallow holes and the plain of Drama, coincides with the general direction of the planes of fractures in distension, imposed by the field of the tectonic constraints. Thus, these particular boundaries conditions of the karst aquifers determine a specific organization of the underground network drainage and reduce the time of its installation especially since the surface flow contributions are significant.

References

Arthaud, F., Choukroune, P., 1972. Méthodes d'analyse de la tectonique cassante à l'aide des microstructures dans les zones peu déformées. Exemple: la plate-forme nord-aquitaine. Revue de l'Institut Français du Pétrole 27 (5), 715—732.

Bakalowicz, M., 1979. Contribution de la géochimie des eaux à la connaissance de l'aquifère karstique et de la karstification. Thèse de Doctorat d'État ès Sciences naturelles, P. et M. Curie Paris-6, Paris, 269pp.

Bakalowicz, M., 1994. Water geochemistry: water quality and dynamics. In: Stanford, J., Gibert, J., Danielopol, D. (Eds.), Groundwater Ecology. Academic Press, pp. 97—127.

Bouchaou, L., Mangin, A., Chauve, P., Mania, J., Aboufirassi, M., 1996. Apports des méthodes hydrodynamiques à l'étude du fonctionnement des aquifères karstiques de l'Atlas de Beni-Mellal (Maroc). Geodinamica Acta (Paris) 9 (4), 170—176.

Box, G.E.P., Jenkins, G.M., Reinsel, G.C., 1994. Time Series Analysis: Forecasting and Control, 3rd ed. Prentice Hall, Englewood Cliffs, NJ, USA.

Chagipanagis, I., 1991. Geological Structure of the Falakro Mountain Area. Ph.D. Thesis, Polytechnical School of Athens, 179pp (in Greek).

Chagipanagis, I., Vouyioukas, D., Theodoridis, A., Papatrechas, C., 2000. Geological study of marbles on the quality determination for the exploitation of marbles. A pilote application on region Granitis—Drama. In: Proceedings of the 2nd Congress ''The Greek Marble'', Thessaloniki, Greece, pp. 35—45.

Dimadi, A., 1988. Comportement hydrogéologique des marbres de la bordure du Rhodope. Hydrogéologie du secteur sud-ouest du massif du Falakro, Macédoine Orientale, Grèce. Ph.D. Thesis, Univ. of Grenoble I, France, pp. 214.

Dinter, D.A., 1994a. Tectonic evolution of the Rhodope Metamorphic Core Complex, Northeastern Greece. Ph.D. Thesis, Massachusetts Institute of Technology, USA, 320pp.

Dinter, D.A., 1994b. Tertiary structural evolution of the southern Rhodope metamorphic province: a fundamental revision. Bulletin of the Geological Society of Greece XXX (1), 79—89.

Doutsos, Th., Ferentinos, G., 1984. Post-Alpine crustal deformation of North Aegean Region (Greece). Geologica Balcanica, Sofia 14 (6), 37—46.

Dray, M., Jusserand, C., Novel, J.P., Zuppi, G.M. 1998. Precipitation in the French and Italian Alps. Air masses circulation and isotopic shadow effect. In: International Symposium on Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere. IAEA, Vienna, Austria, April 14—18, 1997, pp. 107—117.

Drogue, C., 1974. Structure de certains aquifères karstiques d'après les résultats de travaux de forages. Comptes Rendus à l'Académie des Sciences, Paris 278 (D), 2621—2624.

Epitropou, N., Chagipanagis, I., 1987. Contribution à la géologie du massif ouest du Falakro. IGME report, Xanthi, Greece (in Greek).

Eraso, A., 1985. Metodo de prediccion de las direcciones principales de drenaje en el karst. Kobie (serie ciencias naturales), Bilbao, Spain, XV, 1985/86, pp. 1—122.

Eraso, A., 1986. Aplicacion del metodo de prediccion de las direcciones de drenaje al karst de Larra (Navarra, Francia) y el karst del complejo de Go Guarena (Burgos). Journées sur le Karst en Euskadi, San Sebastian, Spain 2, 229—254.

Grillot, J.C., 1979. Structure des systèmes aquifères en milieu fissuré. Contribution méthodologique à cette connaissance. Thèse Doctorat d'État ès Sciences, Laboratoire d'Hydrogéologie, Université des Sciences et Techniques du Languedoc, France, 227pp.

Ivanov, Z., 1988. Aperçu général sur l'évolution géologique et structurale du massif des Rhodopes dans le cadre des Balkanides. Bulletin de la Société Géologique de France IV (2), 227—240.

Jones, C.E., Tarney, J., Baker, J.H., Gerouki, F., 1992. Tertiary granitoids of Rhodope, northern Greece: magmatism related to extensional collapse of the Hellenic Orogen? Tectonophysics 210, 295—314.

Larocque, M., Mangin, A., Razack, M., Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karstic aquifer (Charente, France). Journal of Hydrology 205, 217—231.

Leontiadis, I.L., Payne, B.R., Letsios, A., Papagianni, N., Kakarelis, D., Chadjiorakis, D., 1983. Isotope hydrology study of Kato Nevrokopi of Dramas, Greece. In: International Symposium on Isotope Hydrology in Water Resources Development, IAEA, Vienna, Austria, 12—16 September 1983, pp. 193—206.

Mangin, A., 1975. Contribution à l'étude hydrodynamique des aquifères karstiques. Thèse Doctorat d'État ès Sciences, Univ. of Dijon, France (Annales de Spéléologie 29(3), 283—332; 29(4), 495—601; 30(1), 21—124).

Mangin, A., 1981a. Utilisation des analyses corrélatoire et spectrale dans l'approche des systèmes hydrologiques. Comptes Rendus à l'Académie des Sciences, Paris 293, 401—404.

Mangin, A., 1981b. Apports des analyses corrélatoire et spectrale croisées dans la connaissance des systèmes hydrologiques. Comptes Rendus à l'Académie des Sciences, Paris 293, 1011—1014.

Mangin, A., 1984a. Écoulement en milieu karstique. Annales des Mines 5—6, 135—142.

Mangin, A., 1984b. Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoire et spectrale. Journal of Hydrology 67, 25—43.

Mangin, A., 1985. Progrès récents dans l'étude hydrogéologique des karsts. Stygologia 1 (3), 239—257.

Marinos, P., Dimadi, A., Xidakis, G., Koutitas , C., 1987. Groundwater hydraulics of a large karstic conduit-sinkhole drainage and spring discharge in Drama area, Greece. In: Proceedings of the 2nd multidisciplinary conference on sinkholes and the environmental impact of karst. Orlando, Florida, pp. 261—268.

Marinos, P., Dimadi, A., Xidakis, G., Koutitas , C., 1994. Hydrogeological conditions in the Western Falakro mountain. The hydraulic regime of the karstic spring of the river Aggitis and the Mara cave. In: Proceedings of the 7th Congress of the Geological Society of Greece, vol. XXX, 4, pp. 159—162.

Marsaud, B., 1997. Structure et fonctionnement de la zone noyée des karsts à partir des résultats expérimentaux. Ph.D. Thesis, Université Orsay-Paris Sud. Documents du BRGM, 268, 306pp.

Max, M., 1980. Méthodes et Techniques du Traitement du Signal et Applications aux mesures Physiques, second ed. Masson, Paris, France.

Morales-Juberias, T., Cruz-Sanjulian, J.J., Zafra, P., Olazar, M., Arandes, J.M., 1996. Étude des réponses naturelles du système karstique d'Olalde (Pays Basque): approche de la reconnaissance de sa structure interne. Hydrogéologie 1, 39—51.

Padilla, A., Pulido-Bosch, A., 1995. Study of hydrographs of karst aquifers by means of correlation and cross-spectral analysis. Journal of Hydrology 168, 73—89.

Razack, M., 1978. Contribution à l'étude de la structure des aquifères en roches fissurées. Numérisation et analyse quantitative de la fracturation relevée sur clichés aériens. Thèse Docteur-Ingénieur, Laboratoire d'Hydrogéologie, Université des Sciences et Techniques du Languedoc, France, 124pp.

Razack, M., 1980. Sur la contribution de méthodes d'analyse numérique appliquées à l'étude d'un champ de fractures pour une meilleure connaissance de la structure des réservoirs fissurés. Comptes Rendus à l'Académie des Sciences, Paris 286, 1577—1580.

Rossier, Y., 1985. Exemples d'application d'une méthode d'analyse de la formation. Illustration en pays granitique et calcaire. In: Symposium de Montvillargenne L'approche stochastique des écoulements souterrains, 3—6 Juin 1985, France, pp. 475—486.

Soulios, G., 1985. Contribution à l'étude hydrogéologique des systèmes aquifères karstiques du Pays Hellénique. Science Annales 23, 292 (in Greek).

Soulios, G., 1991. Contribution à l'étude des courbes de récession des sources karstiques: exemples du pays hellénique. Journal of Hydrology 124, 29—42.

Vavliakis, E., Lambrinos, N., Syridis, Th., 1989. The polje of Kato Nevrokopi — Kato Vrondu (the Rila — Rhodope Massif)Geographica Rhodopica, Sofia, 1. Kliment Ohridiski University Press.

Villiers, G. du T. de, 1990. Rainfall variations in mountainous regions. In: Hydrology in Mountainous Regions. Proc. of Two Lausanne Symp., Switzerland, I.A.H.S. Publ. no. 193, pp. 33—41.