ENVIRONMENTAL ISOTOPE DATA IN THE WESTERN THESSALY VALLEY, GREECE. USE OF MATHEMATICAL MODEL FOR QUANTITATIVE EVALUATIONS WITH TRITIUM*

BY

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Abstract.— The present paper deals with the results of an environmental isotopic study in western Thessaly valley, carried out during the period 1968 - 1971. The isotopes used are ^{18}O, D, Tritium, ^{13}C and ^{14}C. By the interpretation and evaluation of these results useful informations as regards the source of recharge, the recharge mechanism and the dynamics of the flow system of the valley are provided.

1. INTRODUCTION

From 1968 to 1971 a demonstration study on the use of environmental isotopes in the hydrological investigation of the Western Thessaly Valley, Greece, was carried out in collaboration by IAEA, N. R. C. Democritus and Greek Institute for Geology and Subsurface Research.

The Western Thessaly Valley is a large northwest-southeast trending nearly flat plain about 70 km long and 30 km wide and ranging from about 90 to 120 metres above sea level.

The major stream, the Pinios River, flows from NNE to SSW and further from W to E. The upper (northwestern) part of the Western Thessaly Valley is called the Kalambaka Basin and its hydrogeology has been described in detail by G. A. KALLERGIS [**1**].

The problems indicated for study by isotopes were the relation between unconfined and confined aquifer systems, their recharge area and, if possible, the velocity of underground water movement.

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2. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS OF THE AREA

2.1. GEOLOGICAL CONDITIONS

Western Thessaly valley represents a part of the «mesohellenic trench» which has been formed by the «tardi» tectonic events of the main Alpidic orogenic phase (middle upper Eocene) during the stage of expansion of the elastic tensions of it.

This «trench» has been emplaced between the Pindic Cordilliera, consisted by sentimentary rocks of Triassic - Eocene age of Pindic geosyncline and the Pelagonic and the Subpelagonic Cordilliera. The Pindic Cordilliera was already entirely emerged in the middle Eocene though the Pelagonian and Subpelagonian Cordillieras emerged during the Maestrichtian Eocene respectively. The Subpelagonic Zone, developed between the Pindic geosyncline and the Pelagonic ridge, comprises sediments of a transition facies between pelagic and reef one and ophiolites as well.

The age of the Subpelagonian formations is Triassic-Eocene. The Pelagonic Zone comprises reef sediments of Latest Paleozoic (?) to Maestrichtian age affected by metamorfism.

The bedrock of the clastic sediments of the fill of the valley and the margin of it as well is consisted by formation of the above mentioned three isopic zones. The Pindic and Subpelagonic Formations (carbonaceous roks - shales - cherts - ophiolites - flysch) cover, mainly, the NN Western Western and Southern margins of the valley. The Pelagonic formations (marbles-schists-gneisses etc.) cover the NEastern margins of the valley. In such a «rocky environment» installed the «mesohellenic trench» which was filled by Eocene-Bourdigalian formations of marine, continental and fluviatil facies, of total thickness, over 1500 m. These formations comprise organogenic limestones, marbles, conglomerates and sandstones.

After the «trench» was filled by the above mentioned formations (Bourdigalian) begun the deposition of terrestrial and/or fluvioterrestrial clastic material. By this way a thick sequence of Plio-pleistocenic-Olocenic clastic deposits (pebbles, cobbles, sands of different grain size, clays, silts and mud in various, each time, percentages of mixture). These clastic deposits are more or less coarse close to the margins of the valley (fans of Pinios river and its tributaries). In these locations pebbles, gravels, and coarse sand predominate.

These clastic deposits become towards the center of the valley less coarse to fine (silts, clays alternated with medium to fine sands). In these Plio-pleistocenic Olocenic formations important aquifers are formed.

2.2. HYDROLOGICAL CONDITIONS

The entire lower part of the W Thessaly valley is occupied by fluviotorrential Plio-Pleistocenic-Olocenic clastic material the size of which diminishes from N to S and from W to E. The fans of Pinios river and its tributaries (Portaikos, Pamissos, Sophaditis, Enipefs) are consisted from coarse loose clastic deposits without considerable vertical grain size changes. Here, importand unconfined aquifers are formed. Towards the center of the valley not only horizontal but also vertical changes of the grain size of the clastic deposits take place.

This results alternation of strata consisted from coarse (medium-fine sand) and fine (silts-clays) material. In this region a perched insignificant unconfined aquifer and successive confined aquifers, are in hydraulic connection with the unconfined aquifers of the fans of Pinios river and its tributaries.

In the transition zone where the marginal unconfined aquifers change into the successive confined ones some springs (Mikron and Megalon Kephalovrisson Springs) are manifested.

Such manifestations (alluvial springs) are also observed in other places of the valley (Springs of Pouliana, Gilanthi etc.).

In the margins of the valley occur some karst springs (Diava, Morava, Voula, Klocotos, Pili, Mouzaki Karst Springs etc.).

3. GENERAL COMMENTS ON THE APPLICATION OF ENVIRONMENTAL ISOTOPES

A concise summary of the use of environmental isotope techniques in hydrological problems is given in references [**2**] and [**8**]. More detailed discussions are contaided in an IAEA Guidebook [**3**]. A brief definition of environmental isotopes (from PAYNE [**2**]) follows:

«Environmental isotopes may be defined as those isotopes, both radioactive and stable, which occur in the environment in varying concentrations and over which the investigator has no direct control. At present, the commonly used environmental isotopes are the stable isotopes deuterium and oxygen-18 and the radioisotopes tritium and carbon-14. The first three isotopes are part of the water molecule and as isotopic tracers constitute the only real water tracers available to the hydrologist. All other water tracers are present in a dissolved form and, therefore, are subject to loss by precipitation, adsorption and exchange.»

To the four commonly used isotopes mentioned above we should add the stable isotope carbon-13. When it is used in conjunction with carbon-14 and geochemical data, it is frequently possible to improve the accuracy of time relationships or «ages» from the carbon-14 results.

3.1. OXYGEN-18 AND DEUTERIUM

The hydrogen and oxygen stable isotope variations found in natural waters often provide evidence of the waters' origin or source. References [**3**, **8**] include a number of comments regarding the application of these stable isotopes to hydrologic studies. Craig [**4**] and Dansgaard [**5**] present more dedailed discussions regarding the principles underlying the occurrence of the oxygen and hydrogen stable isotopes within the hydrologic cycle.

The stable isotopic composition of groundwaters is commonly close to that of the precipitation which infiltrates as recharge. In general, stable isotope variations in more or less contemporaneous groundwaters are most readily related to: 1) differences in temperature of condensation and, hence, often to variations in the altitude at which recharge from precipitation occurs; and 2) distance inland from oceanic sources of moisture. However, in old groundwaters (more than a few thousand years) the oxygen-18 and deuterium variations may result from paleoclimatic differences, especially temperature and moisture variations related to the last major glaciation, which ended about 10,000 or 12,000 years ago.

If part or all of the recharge is from a surface water body (river, lake or local pond) instead of infiltration of precipitation, the oxygen-18 and deuterium are ordinarily «enriched» (i. e. they have a positive or less negative deviation from the standard, SMOW) because of preferential evaporation of the «light» (^{16}O and ^{1}H) isotopes. Thus it is possible to differentiate between directly infiltrtated precipitation and infiltration from surface water bodies that have been subjected to evaporation.

3.2. TRITIUM

Tritium analyses of groundwater samples provide useful information about the age or residence time, and thus the probable time of recharge of the sampled water if it is less than 3 or 4 decades old. In older waters tritium has been reduced by radioactive decay below the limit of detection. Many examples of the use of tritium data in hydrological problems are discussed in reference [**3**].

In general, the residence time indicated by the tritium content of a groudwater sample corresponds to the elapsed time between the occurrence of recharge — that is the time when the rainfall enters the soil and unsaturated zone — and the sample collection time. This is normally the same as the age of the water sample. Such residence time or age representations are approximate only and whereas they are probably reliable as relative age indicators between groundwaters of different localities or different water-bearing zones, they should not be taken as denoting the exact age of a water sample. This is largely because the constant or steady state conditions for recharge assumed for such a representation do not in fact normally occur in nature and because the movement of water underground may be highly irregular. Despite these imperfections, it is often useful to examine the residence time or age indications suggested by tritium data in combination with other isotope and (or) hydrogeological information.

Tritium in the atmosphere is derived from two sources. The first is from cosmic radiation and it accounts for a concentration of about 10 T.U.[1] in precipitation on a world-wide basis (see ref. [**3**], p. 7). The second is a mam-made influence — thermonuclear bomb testing between 1952 and 1963, which introduced very large amounts of tritium into the atmosphere (up to 10,000 or more T.U. in places in the northern hemisphere).

In the Western Thessaly Valley, the tritium contents of groundwater samples range from zero to more than 300 T.U. In general, tritium is found in the groundwaters sampled from springs or wells near the edges of the valley but is absent (or below a readily detectable amount, 1 T.U.) in most boreholes in the middle of the valley[2]. Variations in tritium contents of groundwater samples may occur in the following somewhat oversimplified ways:

a) Spatial variations of precipitations from year to year; local areas might have received unduly large amounts of precipitation in contrast to others receiving little — during the period when infiltration could occur — at times when the tritium concentration in the atmosphere was unusually high.

b) Local variations of infiltration amounts resulting from soil and vegetation differences.

c) Local variations in permeability and (or) thicknesses of the unsaturated zone causing differences in the time required for the high tritium

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[1] 1 T.U. (tritium unit) = 1 atom of tritium per 10^{18} hydrogen atoms.

[2] The presence of measurable tritium in a sample from a deep aquifer borehole that is not located in the aquifer recharge zone, indicates some type of contamination: a) leaks through the casing from a shallow aquifer; b) during sample collection; or c) during the sample analysis. Ordinarily, the latter is detectable from the results of other analyses made at or about the same time.

concentrations of the late thermonuclear bomb test period (1962 - 1964) to reach the unsaturated zone.

Although it is not strictly accurate to designate a single year to mark the onset of contribution from bomb testing to tritium input, because the effects built up gradually through several years in the 1950s and were affected by local differences in the physical environment, for convenience in the following discussions the year 1953 has been used to represent the beginning of the influence of bomb tritium. On the basis of the above generalizations, certain ranges of tritium contents may be related to the residence time or mean age of groundwaters sampled within the past 3 or 4 years; these ranges are as follows:

a) 0 - 3 T. U. — Time-since-recharge ranging from about 15 to 35 or more years (greater than about 35 years for samples having no detectable tritium).

b) 3 - 30 T. U. — Recharge occurring mainly in the early part of the bomb-testing period.

c) Greater than 30 T. U. — Recharge occurring in the latest part of the thermonuclear testing period or after it.

The matching of the above ranges of tritium concentration to recharge times ignores possible mixing effects, such as a certain amount of very recent (last few years) recharge mixed with recharge from more than about 35 years before the sample collection date. It is also based on an assumption of a prethermonuclear or natural level of atmospheric tritium of 10 T. U. (see p. 7, ref.) [**2**], which may not be correct for the Thessaly region. When «age» for a water sample is referred to subsequently in this report, it is with reference to the sample collection date rather than to the present date.

3. 3. CARBON ISOTOPES

The carbon isotopes (carbon-12, carbon-13 and carbon-14) are useful in hydrogeological interpretations mainly because carbon-14 (like tritium) is a radioactive isotope which decays with time. Carbon-14 has a half-life of 5,730 years and thus is useful in studying the hydrological conditions related to waters that are several millenia (rather than a few decades as for tritium) old. Unadjusted radiocarbon ages determined from carbon-14 contents alone are ordinarily greater than true ages because part of the total dissolved carbon species is derived from non-biogenic carbon containing no carbon-14. Taking this into account, the «age» may be adjusted if reliable geochemical data are available.

4. RESULTS OF THE ENVIRONMENTAL DATA - DISCUSSIONS, INTERPRETATIONS AND EVALUATIONS

4. 1. AVAILABLE ISOTOPE DATA

The sampling programme carried out in the Western Thessaly Valley covers the period of October 1968 to July 1971 and includes selected rainfall stations, lysimeters, streams, springs and drilled wells. Periodic samples collected from these sources were analysed for environmental isotopes. All isotopic analyses were carried out in the Isotope Laboratory of the IAEA in Vienna, with the exception of deuterium which was analysed in the Geophysical Isotope Laboratory of the University of Copenhagen. The results of the isotopic analyses from groundwater sources (sampled at wells and springs) are given in Table 4 and isotope data from precipitation stations, lysimeters and streams are given in Table 5. Sampling points in the project area are shown on Maps 1 and 2 together with the results of the isotopic analyses.

The accuracy of the ^{18}O results given is about $\pm 0.2\,‰$ and for dueterium analyses is reported to be $\pm 2\,‰$. The error terms associated with tritium and ^{14}C analyses are given together with the results of individual analyses performed.

4. 2. DISCUSSION OF ISOTOPE DATA

4. 2. 1. **Isotope data on precipitation.**

Periodic samples of precipitation have been collected at two precipitation stations (Chrisomilia and Meteora) and also at four lysimeter stations (Kephalovrisso, Paleomonastiron, Pouliana and Sarakina). In the first block of Fig. 1, $\delta^{18}O$ values of all rainfall samples for each lysimeter station are shown. A wide range of variations between $-2.4\,‰$ and $-12.7\,‰$ is obsevred in the $\delta^{18}O$ content of rain over the project area. The time variation of the $\delta^{18}O$ content of rainfall for each precipitation station and for three of the lysimeter stations is given in Fig. 2. The most common feature observed in Fig. 2 is the seasonal variation of the $\delta^{18}O$ content of rainfall. Depleted values during the winter months and relatively enriched values during the summer months are due to the known dependence of the stable isotopic composition of rain on the temperature at the time of condensation. The only year for which samples are available for all months is 1969, and the plot of $\delta^{18}O$ versus δD for this year is shown on Fig. 3 for the two rainfall stations. Since

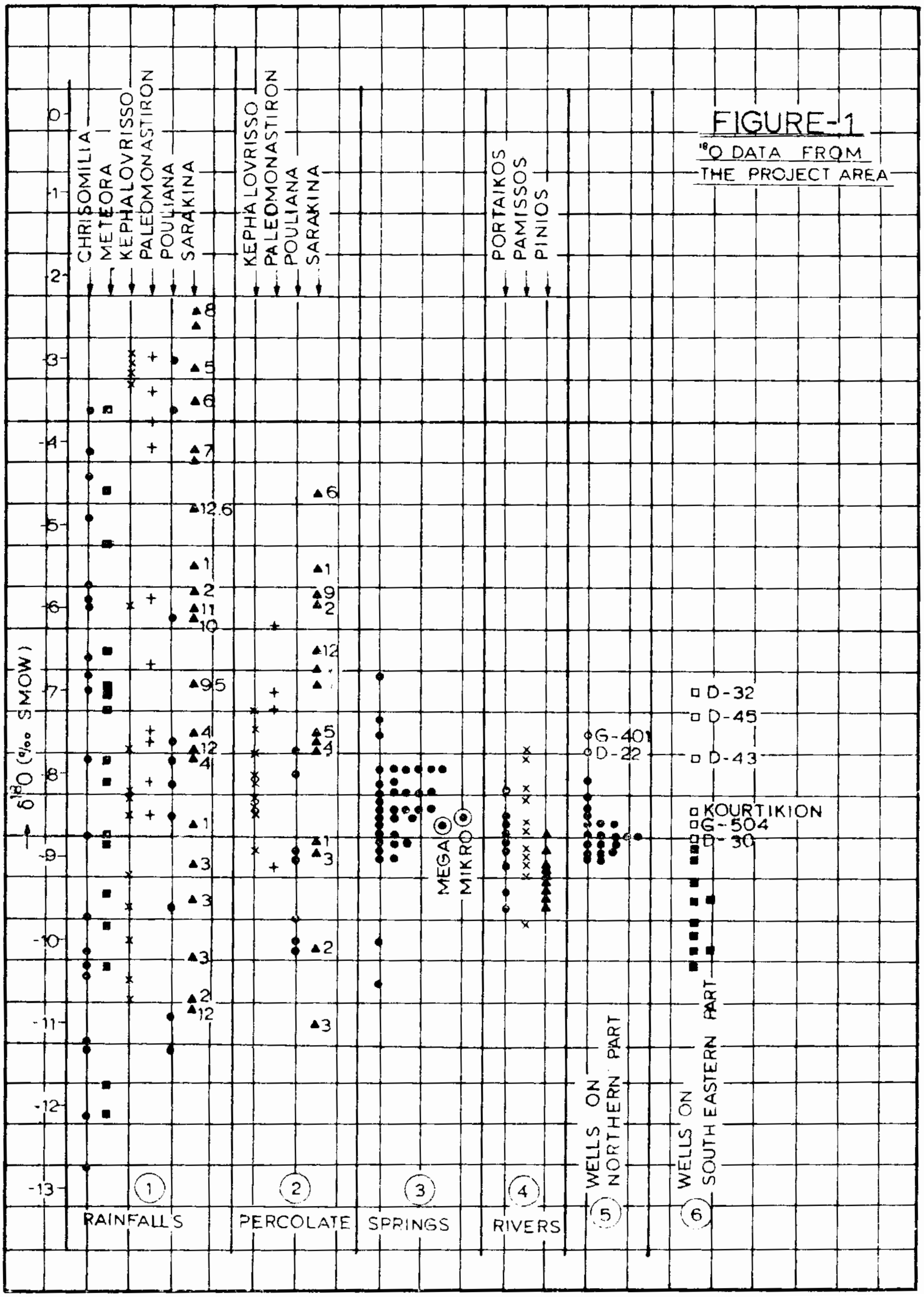


FIGURE-1
18O DATA FROM THE PROJECT AREA
δ18O (‰ SMOW)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
CHRISOMILIA
METEORA
KEPHALOVRISSO
PALEOMONASTIRON
POULIANA
SARAKINA
KEPHALOVRISSO
PALEOMONASTIRON
POULIANA
SARAKINA
PORTAIKOS
PAMISSOS
PINIOS
MEGA
MIKRO
G-401
D-22
D-32
D-45
D-43
KOURTIKION
G-504
D-30
WELLS ON NORTHERN PART
WELLS ON SOUTH EASTERN PART
① RAINFALLS
② PERCOLATE
③ SPRINGS
④ RIVERS
⑤
⑥

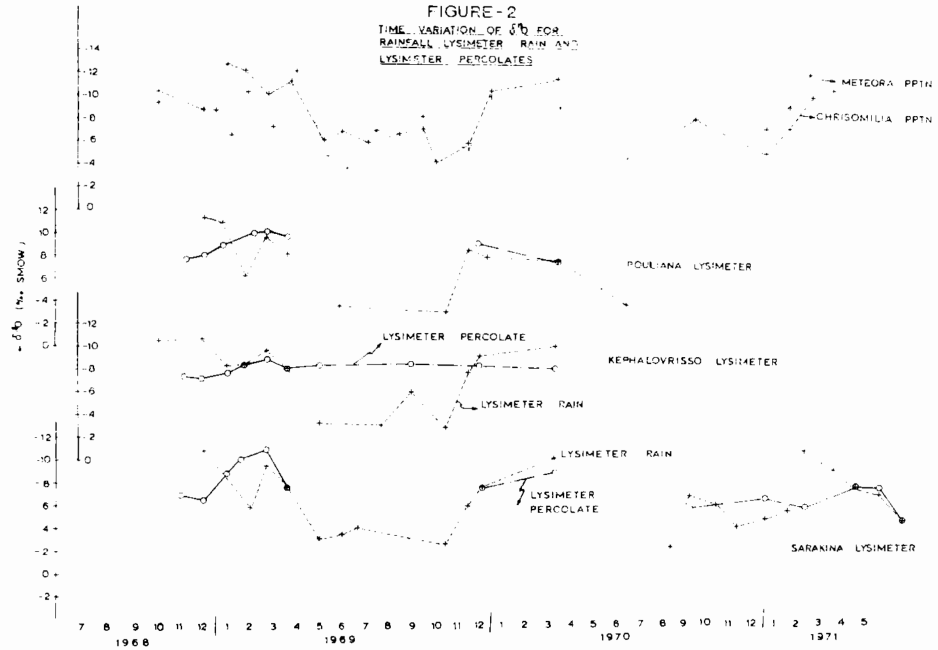


FIGURE - 2
TIME VARIATION OF $\delta^{18}O$ FOR RAINFALL, LYSIMETER RAIN AND LYSIMETER PERCOLATES

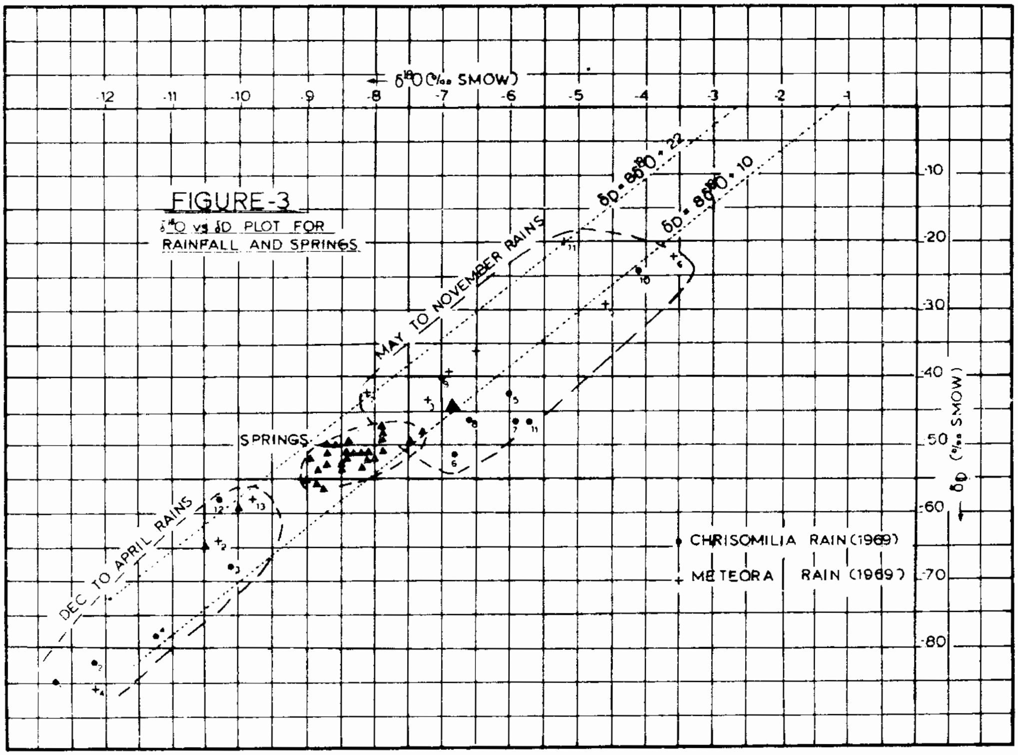


FIGURE-3
$\delta^{18}O$ vs δD PLOT FOR RAINFALL AND SPRINGS

annual variations in the stable isotopic composition of rainfall at a given location are rather small and seasonal variations are rather uniform, it is quite reasonable to assume that the stable isotopic composition of rainfall as given in Fig. 3 (in Figs. 2 and 1 as well) can be used to define the rainfall input into the project area in terms of its stable isotopic composition. As can be seen in Fig. 3, it is possible to distinguish between December to April rains and May to November rains. All the points in Fig. 3 are spread around the normal meteoric line ($\delta D = 8\delta^{18}O + 10$) (None of the samples for which both D and ^{18}O analyses are available show the usual influences such as those resulting from evaporation).

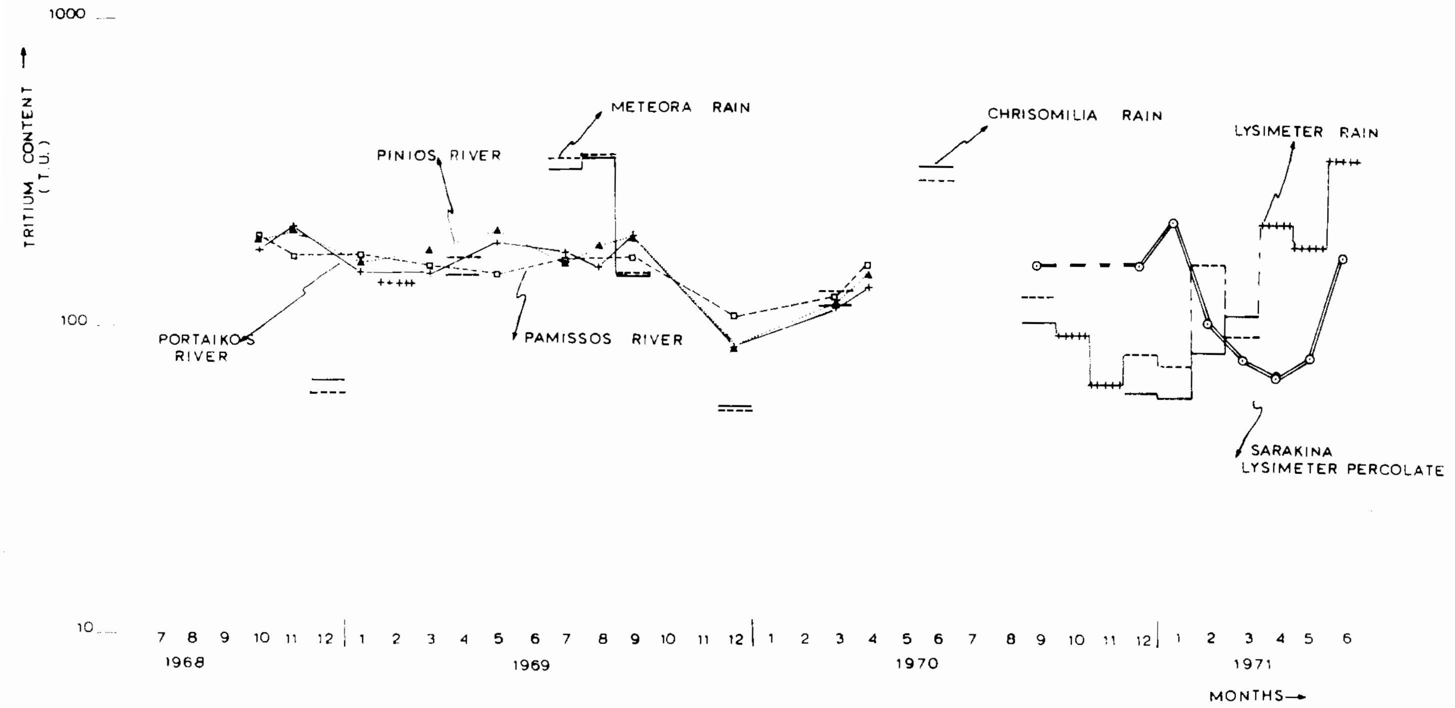
The tritium values available from rainfall stations are shown on Fig. 4 together with those of the rivers. The tritium content of the rain during summer months is about 300 T. U. and about 50 - 80 T. U. during winter months in the last three years.

4. 2. 2. **Isotope data on lysimeters.**

Periodic samples of rainfall and percolate from four lysimeters in the project area have been collected. While rainfall samples collected at these lysimeters, together with those collected from precipitation stations, would enable the definition of the isotopic composition of rainfall input to the project area, the samples collected from lysimeter percolates are a useful means of determining the isotopic composition of that part of rainfall which directly infiltrates from the surface. The second block on Fig. 1 shows the $\delta^{18}O$ values of all available samples from each lysimeter percolate. Time variations of the $\delta^{18}O$ content of lysimeter percolates are shown on Fig. 2 together with the $\delta^{18}O$ content of rainfall observed in each lysimeter. As can be seen from Figs. 1 and 2, there is less time variation in the $\delta^{18}O$ content of percolate compared to that of rainfall, which is certainly due to the storage effect of each lysimeter which results in smoothing of monthly inputs of rainfall. The available isotope data on lysimeter percolates can be used as an approximate index of the isotopic composition of direct infiltration occurring from the surface. Sarakina and Kephalovrisso are the two lysimeters from which a reasonable amount of percolate samples are available. Sarakina lysimeter on the northern part of the project area has a mean $\delta^{18}O$ value of $-7.4^0/_{00}$ for its percolate and Kephalovrisso lysimeter has a mean value of $-8.1^0/_{00}$. Thus, these values could be adopted as the expected mean $\delta^{18}O$ composition

FIGURE-4

TIME VARIATION IN TRITIUM CONTENT OF RAIN AND RIVERS



of a possible direct surface recharge into the groundwater in the northern and central part of the Thessaly Valley. It should be noted that the plots of $\delta^{18}O$ versus δD for those samples where both results are available on lysimeter percolates are well distributed around normal meteoric lines and there is no evaporation effect observed as shown in Fig. 5.

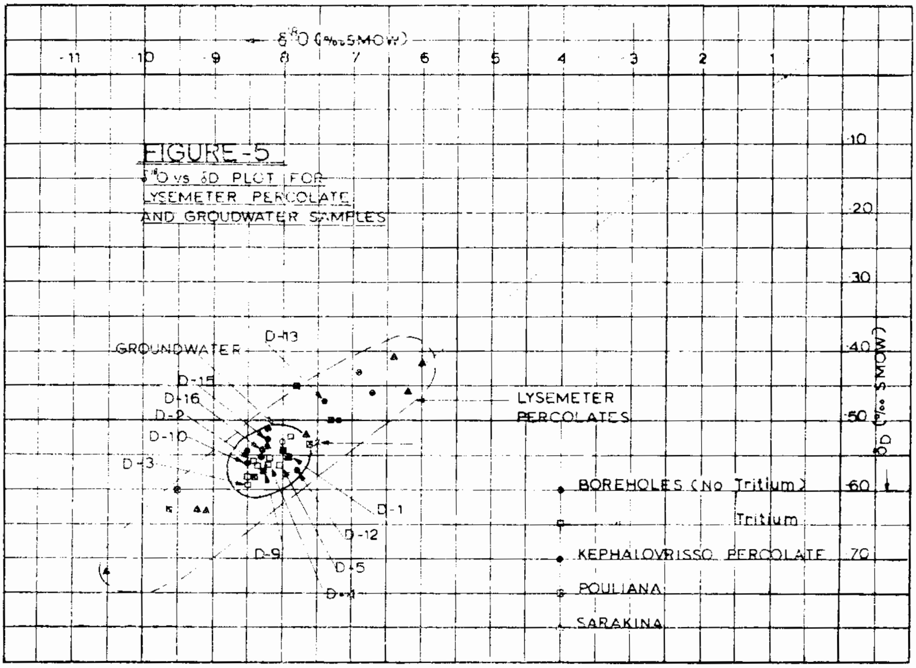


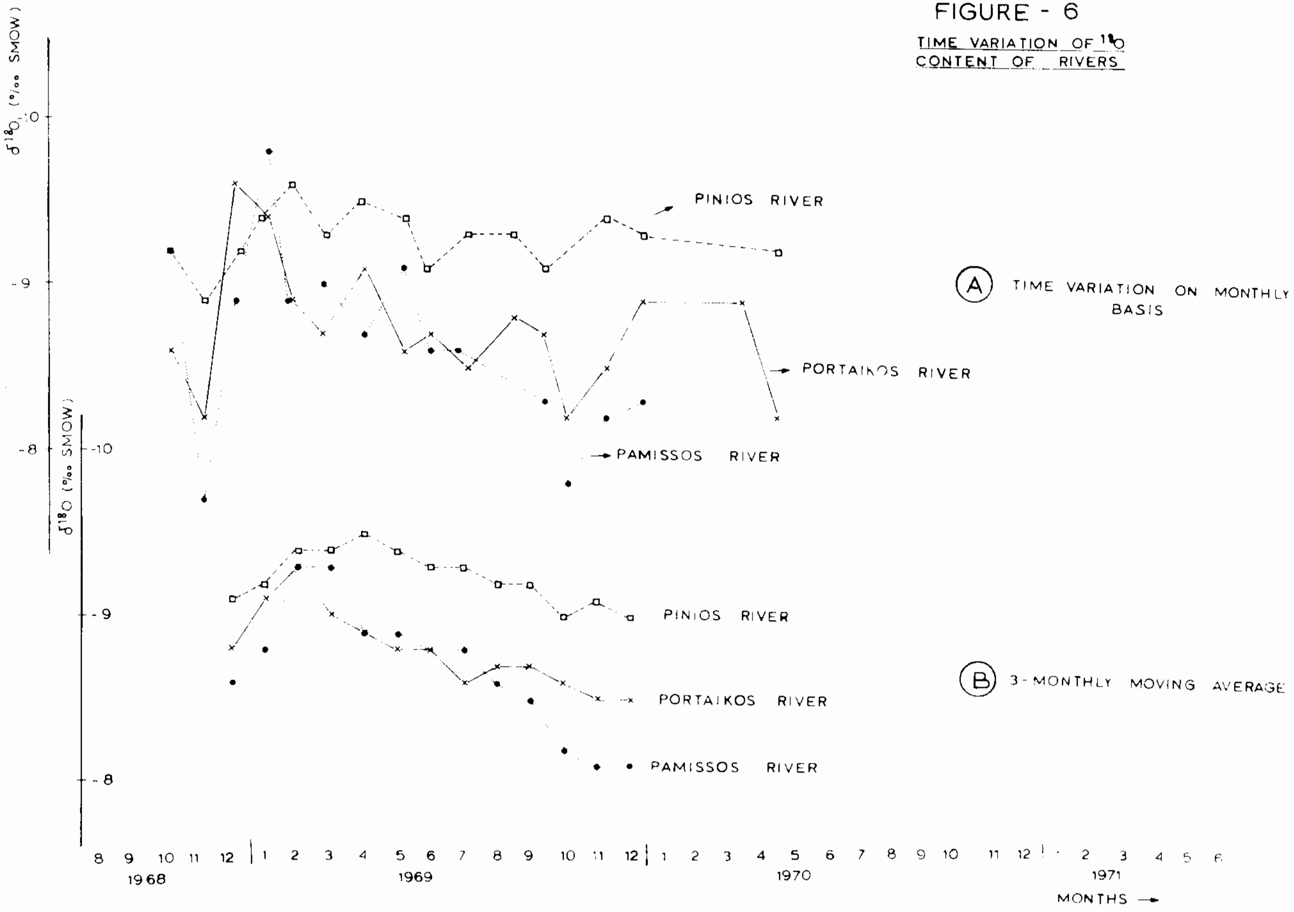
FIGURE-5
$\delta^{18}O$ vs δD PLOT FOR LYSEMETER PERCOLATE AND GROUDWATER SAMPLES

4. 2. 3. **Isotope data on rivers.**

Periodic sampling of the Pinios River and its tributaries Pamissos and Portaikos, were carried out. All available $\delta^{18}O$ values from the rivers are shown on the fourth block of Fig. 1. Considerably less spread of $\delta^{18}O$ values of rivers compared to that of rainfall is evidently due to the storage effects involved in the rainfall-runoff process. The combined effect of storage involved in the base flow component and channel storage involved in the direct runoff component, together with overall mixing, results in a more uniform isotopic composition of river flows and the wide fluctuations of the $\delta^{18}O$ input from rainfall are smoothed out. The time variations of $\delta^{18}O$ in the three rivers are shown on Fig. 6. It should be noted that Portaikos and Pamissos rivers have very similar $\delta^{18}O$

FIGURE - 6

TIME VARIATION OF ^{18}O CONTENT OF RIVERS



contents and similar time variations whereas Pinios River has a slightly depleted $\delta^{18}O$ content as can be seen on Figs. 1 and 6. The second plot on Fig. 6 shows three-months moving averages for the $\delta^{18}O$ content of each river. This type of plotting eliminates wide fluctuations from one month to another, but preserves the seasonal variation. As can be seen from Fig. 6, the curve for the Pinios River is always above the other two and clearly indicates its comparatively depleted $\delta^{18}O$ content. This should be due to the geographic and topographic orientation of their drainage areas. The drainage areas of the Pamissos and Portaikos rivers must have comparable altitudes whereas the Pinios River must be draining either higher altitudes or, if they should have their drainage areas located at similar altitudes, the relative contribution of higher altitudes must be a larger proportion for the Pinios River than for the Pamissos and Portaikos rivers. The mean $\delta^{18}O$ content of the Pamissos and Portaikos rivers is $-8.7\,^0/_{00}$ whereas the Pinios River has a mean $\delta^{18}O$ content of $-9.2\,^0/_{00}$. These values can be adopted as means of studying the possible contribution of these

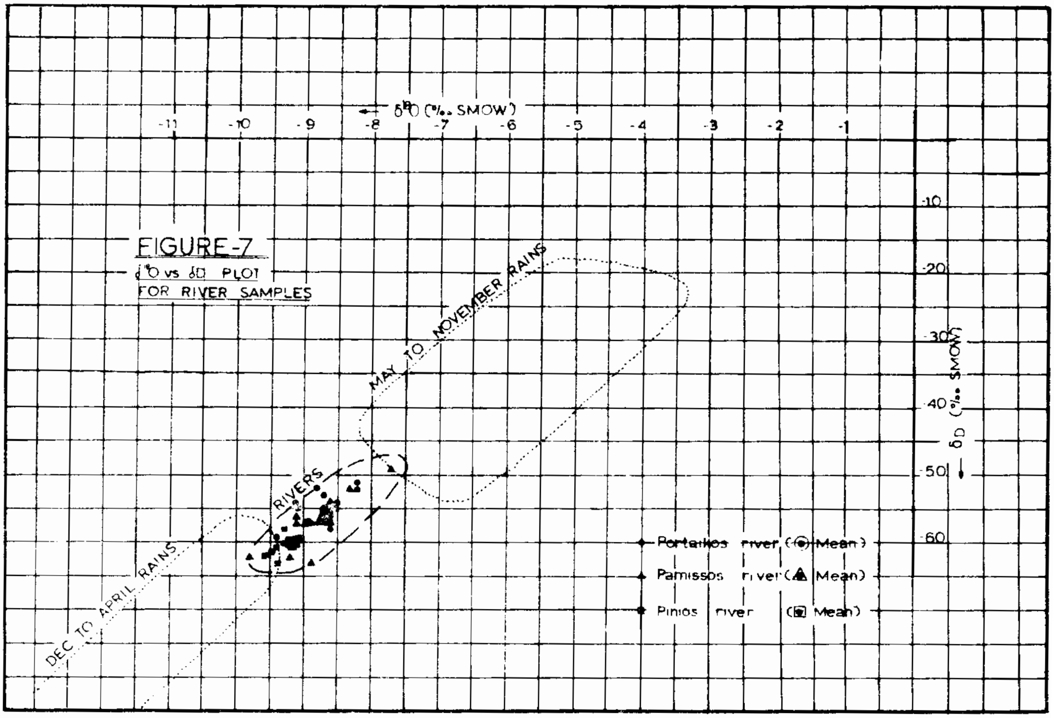


FIGURE-7
$\delta^{18}O$ vs δD PLOT
FOR RIVER SAMPLES

rivers to the recharge of the aquifers in the Thessaly Valley. Plots of $\delta^{18}O$ versus δD for river samples are given in Fig. 7. All the points are quite close to the meteoric line and they are grouped between the rains representing two different seasons, as should be expected. The time variation of the tritium content in these rivers is shown on Fig. 4, together with that of rainfall. The above mentioned smoothing effect can be clearly seen on Fig. 4, also that the rivers have a rather uniform tritium content of about 150 - 200 T. U., except in December 1969, when the direct surface component was probably the major part of the river flow due to higher rainfall occurring in that month.

4. 2. 4. **Isotope data on springs and wells.**

The isotope data collected from groundwater sources include widely scattered wells tapping different horizons and various springs in the project area. The stable isotopic composition of these sources enabled the study of the recharge mechanism and the source of recharge in the groundwater basin of the Thessaly Valley. Tritium and ^{14}C samples collected from these sources have been used to study the hydrodynamics of the system and enabled the evaluation of transit time involved in the groundwater movement. Discussions presented in the above paragraphs were aimed at the determination of indices for the isotopic composition of various possible contributing components to the flow system of the Thessaly basin. Thus, a detailed discussion of the isotope data from springs and wells and findings of the isotope study based on the interpretations and evaluations will be given in the next part.

4. 3. INTERPRETATIONS AND EVALUATIONS

4. 3. 1. **General remarks on the representativity of samples.**

In sampling groundwater reservoirs from boreholes, especially where more than one (or several) water-yielding horizons have been tapped, it is not ordinarily possible to know which layer contributes most of the water to the sample. Thus, ideally in trying to relate the isotopic compositions of samples from different boreholes to each other, an attempt to evaluate the probable mixing of water from different layers should be made.

The discharge of springs in areas of large or moderate topographic relief normally represents a mixture of a sizeable part of an aquifer.

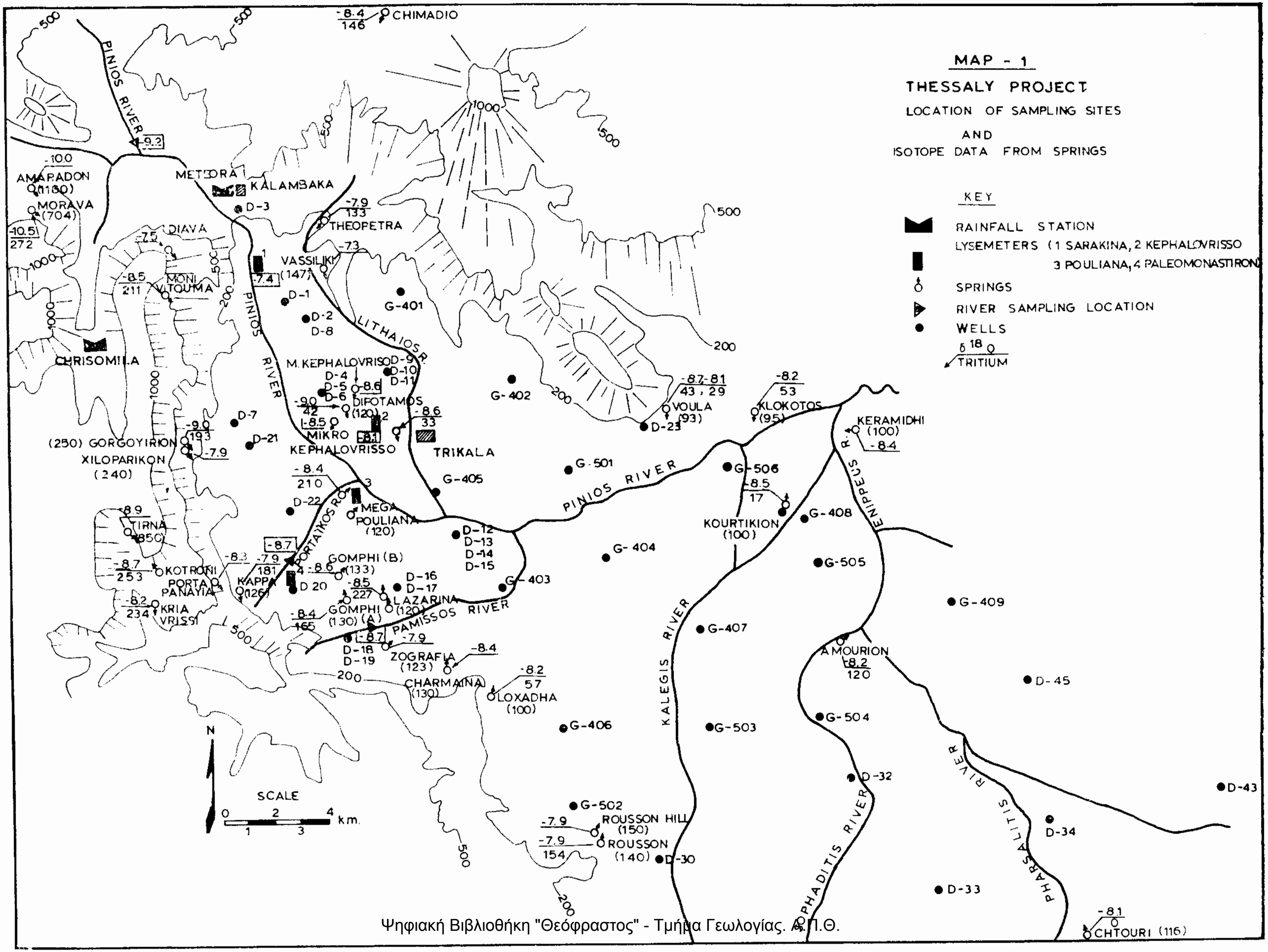
A spring located on alluvial plains, on the other hand, may be discharging mostly from a few horizons and may, or may not, yield waters of a composition similar to that of springs nearby boreholes that yield primarily from deeper layers. Springs that yield primarily from only shallow upper horizons, however, would be expected to show seasonal variations in isotopic composition in comparison to those where the discharge represents a mixture of most of the saturated thickness of the alluvial aquifer.

4. 3. 2. **Isotope data on wells and springs - Interpretations and evalutations.**

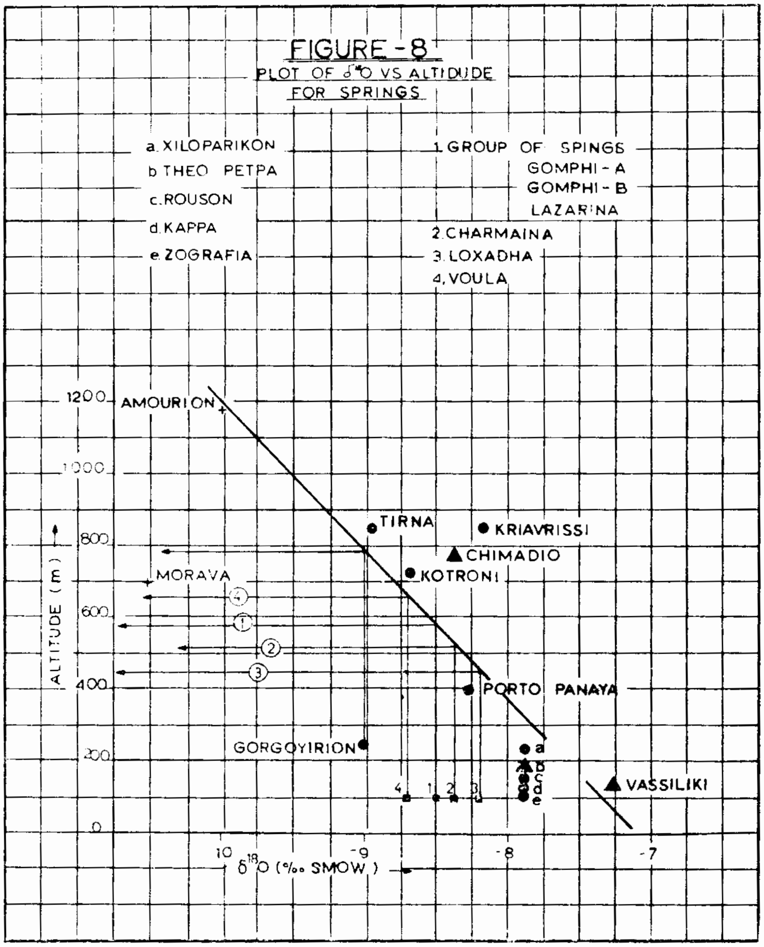
4.3.2.1. **Springs.**

The locations of sampled springs are shown on Map 1 together with $\delta^{18}O$ and tritium values for each spring. The location of rainfall stations, lysimeter stations and sampling points for streams are also shown on Map 1 together with their mean $\delta^{18}O$ values discussed in the above paragraphs.

In the third block of Fig. 1, $\delta^{18}O$ values of all springs are shown. Most of the springs have $\delta^{18}O$ values between -8.0 to $-9.0\,^{0}/_{00}$ while a few have more enriched and a few have more depleted values which reflects either the altitude of their respective recharge areas or their source of recharge, or both. The $\delta^{18}O$ versus δD plot for those spring for which both analyses are available is shown on Fig. 3. The relatively small variations of $\delta^{18}O$ values observed in springs as compared to that of rainfall (see Figs. 1 and 3) are again due to the storage effect associated with springs where the wide fluctuations of rainfall input are smoothed out. A more quantitative interpretation of the isotope data requires that consideration be given to various factors such as location, altitude, etc. of each spring. A plot of $\delta^{18}O$ versus altitude for springs located in the western part of the project area is shown in Fig. 8. The stable isotopic composition of a spring generally reflects the integrated effect of rainfall input occurring at altitudes higher than that of the spring. Springs included in this plot are those located in the western mountaneous region or at the foothills where the most probable recharge is from adjacent highlands. The line defining the relationship between $\delta^{18}O$ content and altitude, as given in Fig. 8, is developed from values of springs Kappa, Porta Panayia, Kotroni, Tirna, Xiloparikon, Amaradon, and has a slope of $-0.2\,^{0}/_{00}$ per 100 m which is close to the generally observed altitude effect. The springs in the northern mountaneous region, namely Vassiliki, Theopetra and Chimadio also agree with the line given


MAP - 1
THESSALY PROJECT
LOCATION OF SAMPLING SITES
AND
ISOTOPE DATA FROM SPRINGS
KEY
RAINFALL STATION
LYSEMETERS (1 SARAKINA, 2 KEPHALOVRISSO
3 POULIANA, 4 PALEOMONASTIRON)
SPRINGS
RIVER SAMPLING LOCATION
WELLS
δ 18 O
TRITIUM
-8.4 146 CHIMADIO
PINIOS RIVER
-9.2
METEORA
KALAMBAKA
D-3
-7.9 133 THEOPETRA
-10.0 AMARADON (1100)
MORAVA (704)
-10.5 272
-7.5 DIAVA
-8.5 211 MONI VITOUMA
VASSILIKI (147)
-7.3
-7.4
D-1
D-2
D-8
G-401
LITHAIOS R.
CHRISOMILA
PINIOS RIVER
M. KEPHALOVRISSO
D-4
D-5
D-6
D-9
D-10
D-11
-8.6
-9.0 42
DIPOTAMOS (120)
-8.6 33
-8.5
MIKRO KEPHALOVRISSO
-8.1
TRIKALA
G-402
-8.7 -8.1 43, 29 VOULA (93)
D-23
-8.2 53 KLOKOTOS (95)
KERAMIDHI (100) -8.4
D-7
D-21
(250) GORGOYIRION -9.0 193
XILOPARIKON (240) -7.9
-8.4 210
D-22
PORTAIKOS R.
MEGA POULIANA (120)
G-405
G-501
PINIOS RIVER
G-506
-8.5 17
KOURTIKION (100)
G-408
ENIPPEUS R.
-8.9 TIRNA (850)
-8.7 253 KOTRONI
-8.3 PORTA PANAYIA
-8.7
-7.9 181 KAPPA (126)
-8.6 GOMPHI (B) (133)
D 20
D-16
D-17
D-12
D-13
D-14
D-15
G-404
G-403
G-505
G-409
-8.2 234 KRIA VRISSI
-8.5 227 LAZARINA (120)
-8.4 165 GOMPHI (130) (A)
PAMISSOS RIVER
-8.7
D-18
D-19
-7.9 ZOGRAFIA (123)
-8.4
CHARMAINA (130)
-8.2 57 LOXADHA (100)
G-407
KALEGIS RIVER
AMOURION -8.2 120
D-45
G-406
G-503
G-504
N
SCALE 0 2 4 km. 1 3
D-32
PHADITIS RIVER
PHARSALITIS RIVER
D-43
G-502
-7.9 ROUSSON HILL (150)
-7.9 154 ROUSSON (140)
D-30
D-34
D-33
-8.1 CHTOURI (116)
500
1000
200

in Fig. 8. Similarly, the springs Zografia, Rousson and Rousson Hill in the southern part of the area are close to the line. Thus, the $\delta^{18}O$ versus altitude relationship developed from springs located in the mountaneous highlands, or at the foothills where the only contributing recharge is most probably from the adjacent highlands, can be taken to be valid for



the northwestern Thessaly area (Kalambaka basin) and the line given on Fig. 8 can be used to study the altitudes of recharge sreas for other springs located in the valley.

As can be seen from Fig. 8, the $\delta^{18}O$ value of Kria Vrissi Spring at 850 m altitude is too much off the line and, apparently, this is due to different sampling times of the spring. Considering the very high tritium contents of all the springs shown on Fig. 8, the transit time of the water recharging these springs must be very short and thus, the $\delta^{18}O$ content of the Kria Vrissi Spring reflects input that occurred close to its time of sampling which differs from all others in the area. The $\delta^{18}O$ content of springs Gorgoyirion and Morava, which are significantly depleted compared to those at comparable altitudes in the same area, is evidence for their recharge area being at higher altitudes. The line given in Fig. 8 indicates that the altitude of the recharge area is higher than 800 m for Gorgoyirion Spring and 1200 - 1300 m for Morava Spring.

For the springs located in the alluvium valley, the same type of evaluation can be made regarding the altitude of their respective recharge areas. However, the use of $\delta^{18}O$ versus altitude relation given in Fig. 8 assumes that the only contributing recharge is laterally from the adjacent highlands. For springs which are located close to the foothills in the valley, such an assumption might be valid, but for springs located near the center of the alluvium valley, a possible contribution of recharge directly from the surface or from the rivers must also be taken into account. Considering, for example, the group of springs Gomphi-A, Gomphi-B and Lazarina, their similar $\delta^{18}O$ value of about $-8.5\ ^0/_{00}$ would indicate that their recharge areas are at an altitude higher than 600 m, as a lateral contribution from the adjacent mountaneous region. Considering their location between the tributaries Pamissos and Portaikos, a possible contribution of these streams or a possible direct recharge through the surface cannot be excluded. However, of these two other possible contributions, if there is any, the rivers must be the more probable one in view of the rather depleted values of these springs comparable to that of the rivers. Thus, any hypothesis of a river contribution to these springs would enable the following evaluations to be made:

a) assuming that the $\delta^{18}O$ content of a spring in the alluvium, where the recharge is only from the adjacent highlands, would be abut $-7.9\ ^0/_{00}$ as observed in the Kappa Spring (which is close to these three springs),

b) knowing that the tributaries Pamissos and Portaikos have a mean $\delta^{18}O$ content of $-8.7\ ^0/_{00}$,

the values observed in the Gomphi and Lazarina Springs, which is about $-8.5\ ^0/_{00}$, would result in 80 $^0/_0$ of river contribution to these springs. As can be seen from the above example, a realistic interpretation of the $\delta^{18}O$ values observed in the springs located in the alluvium valley would require a more detailed hydrogeological knowledge of the area. Any convincing hydrogeological evidence to eliminate contribution from rivers would then result in the interpretation given earlier regarding their recharge areas being located at altitudes higher than 600 m. Similar considerations apply to other springs in the project area. The $\delta^{18}O$

value of — 8.4 $^{0}/_{00}$ observed in spring Mega Pouliana, which is quite close to the Portaikos River should be evidence of a probable contribution from the river. The most probable interpretation for springs Charmaina and Loxadha with their $\delta^{18}O$ values of — 8.4 $^{0}/_{00}$ and — 8.2 $^{0}/_{00}$ is that their recharge areas are higher than 500 and 400 m respectively. Spring Voula on the eastern part of the basin, being located close to the foothills of the nortern mountaneous region would have to have its recharge area at an elevation higher than 700 m. (Actually there are two samples collected from this spring at different times. The value of — 0.8 $^{0}/_{00}$ from the first sampling is used since that is the one having a sampling time corresponding to the others. The significant change in the $\delta^{18}O$ content should be due to the rapid response of the spring to rainfall input as evidenced by its high tritium content). The $\delta^{18}O$ values observed in springs Mega - Kephalovrisson, Micro - Kephalovrisson and Dipotamos, which are all located in the central part of the alluvium valley, are of particular interest. Table 1 shows the $\delta^{18}O$ and tritium data from the first two which are located not far from where the generally coarse - grained and unconfined valley fill of the upstream section grades into finer valley fill containing confining beds.

TABLE 1.

Sample collection Date	Tritium in T.U.	Deuterium $^{0}/_{00}$ from SMOW	Oxygen - 18 $^{0}/_{00}$ from SMOW
Mega - Kephalovrisson			
12.11.68	161 ± 6	— 44	— 6.8 *)
9. 3.71	224 ± 16		— 8.2
30. 4.71	231 ± 13		— 8.8
29. 5.71	225 ± 8		— 8.7
20. 7.71	222 ± 9		— 8.8
9.10.71	223 ± 10		
Micro - Kephalovrisson			
12. 9.68	260 ± 9	— 56	— 8.6
12.11.68	252 ± 9	— 55	— 8.8
9. 3.71	192 ± 8		— 8.1
29. 5.71	212 ± 8		— 8.5
9.10.71	187 ± 10		

Considering the location of these springs and the rather depleted $\delta^{18}O$ content, all possible contributing components should be considered, namely :

a) recharge from the northern highlands,
b) recharge from the Pinios River,
c) local recharge as direct infiltration of the rain falling on the coarse alluvium fill.

The stable isotopic composition of each of the above possible contributing components has already been defined in previous paragraphs. That is :

a) Using the $\delta^{18}O$ versus altitude relationship developed in Fig. 8, it is possible to determine the average altitude of their recharge area if the first hypothesis should be the only contributing component.

b) The mean $\delta^{18}O$ content of the Pinios River is determined to be $-9.2\,^0/_{00}$.

c) Direct recharge occurring from the surface has a mean $\delta^{18}O$ content of $-7.4\,^0/_{00}$ as obtained from the Sarakina lysimeter percolate, and $-8.1\,^0/_{00}$ as obtained from the Kephalovrisso lysimeter percolate. However, considering that any direct recharge of these springs should mainly be on the northern part of the valley, the Sarakina lysimeter is more representative and, in view of the fact a much higher number of samples was collected from the percolate, its mean $\delta^{18}O$ value of $-7.4\,^0/_{00}$ should be used to represent the stable isotopic composition of the direct recharge.

Therefore, knowing the stable isotopic composition of these three springs, on the other hand, the relative importance of different recharge components can be studied.

As can be seen from Table 1, Mega-Kephalovrisson has a mean $\delta^{18}O$ content of $-8.62\,^0/_{00}$ (excluding the sample of 12.11.1968[3]) and Micro-Kephalovrisson has a mean $\delta^{18}O$ value of $-8.5\,^0/_{00}$. The only sample available from the Dipotamos Spring has $\delta^{18}O = -9.0\,^0/_{00}$.

If the first component is the only one responsible for recharging these springs, the stable isotope data would indicate that springs Mega-Kephalovrisson and Micro-Kephalovrisson have their recharge areas at comparable altitudes which should be higher than 600 m, and Dipotamos Spring has its recharge area at an elevation higher than 800 m. However, considering the rather uniform $\delta^{18}O$ content at different

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[3] It is likely that this sample was collected when and from where it could be spring water mixed with some evaporated spring-pool water.

sampling times and the quite high tritium content of springs (for Mega-Kephalovrisson and Micro-Kephalovrisson) it seems to be very unlikely that recharge to these springs is only from the northern highlands and that water falling on the mountains follows an underground path to reach these springs. The reasoning behind this is, that the very high tritium content observed in these springs (Mega-Kephalovrisson and Micro-Kephalovrisson) indicates that the transit time of recharging water is short. Thus, one would, accordingly, expect more fluctuations in both $\delta^{18}O$ and tritium content as well, to reflect the known large time variations of the $\delta^{18}O$ and tritium content of rainfall. Therefore, it seems to be the case that the source of recharge to these springs should not only be from the adjacent highlands, and it is much more likely that the Pinios River and direct recharge on the valley also contribute significantly. The rather uniform $\delta^{18}O$ content observed in the Pinios River and the proximity of these springs to the Pinios River and its tributary makes it quite probable that the Pinios River contributes significantly to the recharge of these springs. Thus, if the second and third components are the two which are responsible for recharging these springs, the following - quantitative estimate can be made :

If: C_S = the $\delta^{18}O$ content of the spring,
C_{PR} = the $\delta^{18}O$ content of the Pinios River,
C_{DR} = the $\delta^{18}O$ content of the direct recharge
and f = the fraction of the Pinios River water recharging the springs,

the material balance equation will be:

$$f \times C_{PR} + (1 - f)\, C_{DR} = C_S$$

and, solving «f»

$$f = \frac{C_S - C_{DR}}{C_{PR} - C_{DR}}$$

thus, replacing the known values of

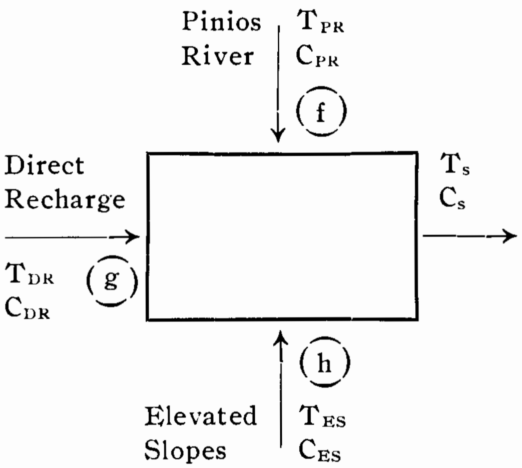
$C_S = -8.5\,^0/_{00}$ for Micro-Kephalovrisson Spring
$C_{PR} = -9.2\,^0/_{00}$ for Pinios River
$C_{DR} = -7.4\,^0/_{00}$ for direct recharge

the fraction of recharge occuring from the Pinios River would be:

$$f = \frac{-8.5 + 7.4}{-9.2 + 7.4} = \frac{-1.1}{-1.8} = \cdot 60$$

Therefore, if the Pinios River and direct recharge are the two components responsible for recharging the springs, the contribution of the Pinios River and direct recharge would be about 60% and 40%, respectively for Micro-Kephalovrisson Spring. The same range of proportions applies to Mega-Kephalovrisson Spring considering its $\delta^{18}O$ to be very close to that of Micro-Kephalovrisson. Similar evaluations would result in 90% of the river contribution and 10% direct recharge contribution for the Dipotamos Spring.

One may even consider further quantitative evaluations of fractional contributions if all three above mentioned recharge components were responsible for recharge of the springs. In this case, there would be three unknown fractions contributed by the possible recharge sources and this requires three equations to be developed. The third equation required can be written for the material balance of the tritium contents observed.



If: f, g, h = the fraction of water recharged from the Pinios River, direct recharge and elevated slopes, respectively, C_{PR}, C_{DR}, C_{ES} are the stable isotopic composition of each recharging componed in the same order as above, T_{PR}, T_{DR}, T_{ES} = the tritium content of each recharging component in the same order as above. C_s and T_s are the $\delta^{18}O$ and tritium content of springs, respectively.

The following equations can be written:

$$f + g + h = 1$$

$$f \times C_{PR} + g \times C_{DR} + hC_{ES} = C_s$$

$$f \times T_{PR} + g \times T_{DR} + hT_{ES} = T_s$$

To solve the above equations for f, g and h it is necessary to know the C_{PR}, C_{DR}, C_{ES}, C_s and T_{PR}, T_{DR}, T_{ES} and T_s values. From the available isotopic data, the following mean values can be assigned to each of these parameters:

$C_{PR} = -9.2$ ‰ $C_{DR} = -7.4$ ‰
$C_{ES} = -7.9$ ‰ (As taken from Spring Theopetra at 190 m on the northern part of the area)
$C_{S} = -8.5$ ‰ (Micro - Kephalovrisson Spring)
$T_{PR} = 180$ T. U. (average observed in Fig. 4)
$T_{DR} = 250$ T. U. (assumed considering level of tritium in rain - Fig. 4)
$T_{ES} = 130$ T. U. (from Spring Theopetra)
$T_{S} = 225$ T. U. (average observed in Micro - Kephalovrisson and Mega - Kephalovrisson Springs).

The use of tritium contents in such a material balance equation assumes the residence time of water in each contributing component system to be short enough to permit that the radioactive decay of tritium be neglected. Quite high tritium values observed allow such an assumption to be a valid hypothesis.

Substituting the above adopted values for each parameter in the above given equation, solving f, g and h would give:

$f = 66$ % contribution from the Pinios River
$g = 52$ % contribution from direct recharge
$h = -18$ % contribution from elevated slopes.

As can be seen from the above computed values, a contribution from elevated slopes does not seem possible. (The negative value obtained for the proportion of recharge coming from elevated slopes has no physical meaning indicating that there can be no contribution from elevated slopes). It should be mentioned that the above quantitative evaluations depend very much on the values assigned to different parameters and they are only estimated values from the available isotope data. Particularly, the stable isotopic composition and tritium content of the recharge component from elevated slopes are taken to be equivalent to that of Theopetra Spring. This assumes that the values observed in this spring reflect the integrated effect of all of the above highlands and thus, any recharge flowing further south would have the same isotopic composition as that of Theopetra Spring. Though this would generally be valid, we should consider that the spring might be tapping a local perched aquifer and thus the values observed would not be representative of the true situation. However, considering that the values observed in some other springs at the foothills of the western mountaneous region are also close to that of Theopetra Spring, it is quite probable that its isotopic composition reflects the integrated effect of water infiltrating from elevated slopes. The available isotope data suggest that recharge to the springs in the coarse-grained central alluvium valley, of which Micro-Kephalovrisson and Mega-Kephalovrisson are of particular significance, takes place mainly from the Pinios River and/or its tributaries and as direct surface recharge from the rain falling on the valley.

For the springs in the eastern Thessaly area as well, rather depleted $\delta^{18}O$ values observed suggest a possible contribution from adjacent rivers. These include Kourtikion, Keramidhi, Klokotos and Amourion. Thus, it seems to be the case that in all Thessaly Valley springs located in the central part receive much of their recharge from adjacent rivers. This fact should be taken into account in studying shallow groundwater in the valley.

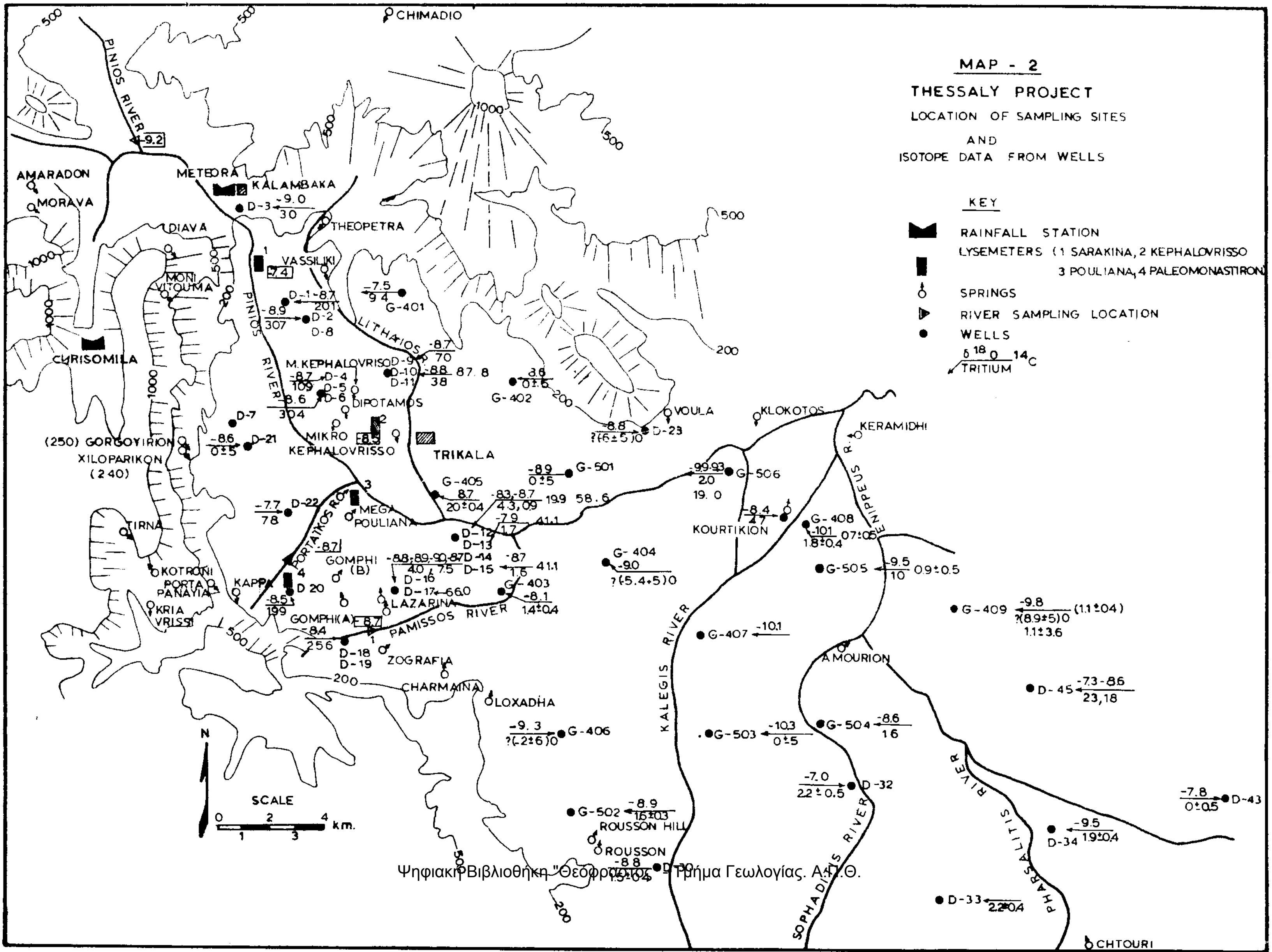
Quantitative evaluations regarding the transit time of flow based on the available tritium data are given together with those of wells after discussing the stable isotope data of drilled wells.

4.3.2.2. **Wells.**

The location of sampled wells is shown on Map 2, together with $\delta^{18}O$, tritium and ^{14}C values. In the last two blocks of Fig. 1, all available $\delta^{18}O$ data from the wells are given. As can be seen from Fig. 1, the stable isotopic composition of the wells located in the western and northern part of the area are, in general, significantly different from those located in the south-eastern part. (The boundary of these two areas is shown on Map 2). Thus, the difference in the stable isotopic composition of wells in these two areas is evidence of a different recharge mechanism for the aquifers.

The wells located in the western and northern part of the area have rather uniform stable isotopic compositions varying between —8.0 ‰ and — 9.0 ‰ with two exceptions, D-22 and G-401, which have relatively enriched values.

A plot of $\delta^{18}O$ versus δD for groundwater samples is shown on Fig. 5. The wells having both $\delta^{18}O$ and δD analyses are all located in the western and northern part of the area. Thus, the grouping of groundwater samples as shown in Fig. 5 reflects the above mentioned uniform stable isotopic composition. On Fig. 5 a plot of available $\delta^{18}O$ versus δD values for all lysimeter percolates is also shown to enable the comparison with groundwater for a possible interpretation regarding the pro-



MAP - 2

THESSALY PROJECT

LOCATION OF SAMPLING SITES

AND

ISOTOPE DATA FROM WELLS

bable contribution of direct surface recharge to groundwater. Fig. 9 is a plot of $\delta^{18}O$ versus δD where the range of stable isotope values observed in all different sources is shown to enable the study of a possible recharge source for groundwater in the project area.

It can be quite clearly seen from Fig. 9, that the wide range of variations in the stable isotopic composition of rainfall input has been smoothed out to various degrees due to the storage and mixing effect involved. The grouping shown on Fig. 9 reflects the respective volume/inflow and/or volume/outflow ratios of different storage elements involved and, as would be expected, the groundwater is the system where the smoothing is most important. The range of values shown on Fig. 9 for lysimeter percolates as an index of the direct recharge component, for rivers as a possible contributing recharge component and for springs as an index to a possible contribution from surrounding highlands, all overlap each other and it does not enable the distinction of any of them as the responsible recharge source. Thus, from the available stable isotope data it is possible that the groundwater in the western and northern part of the Thessaly Valley is being recharged by any of the propable

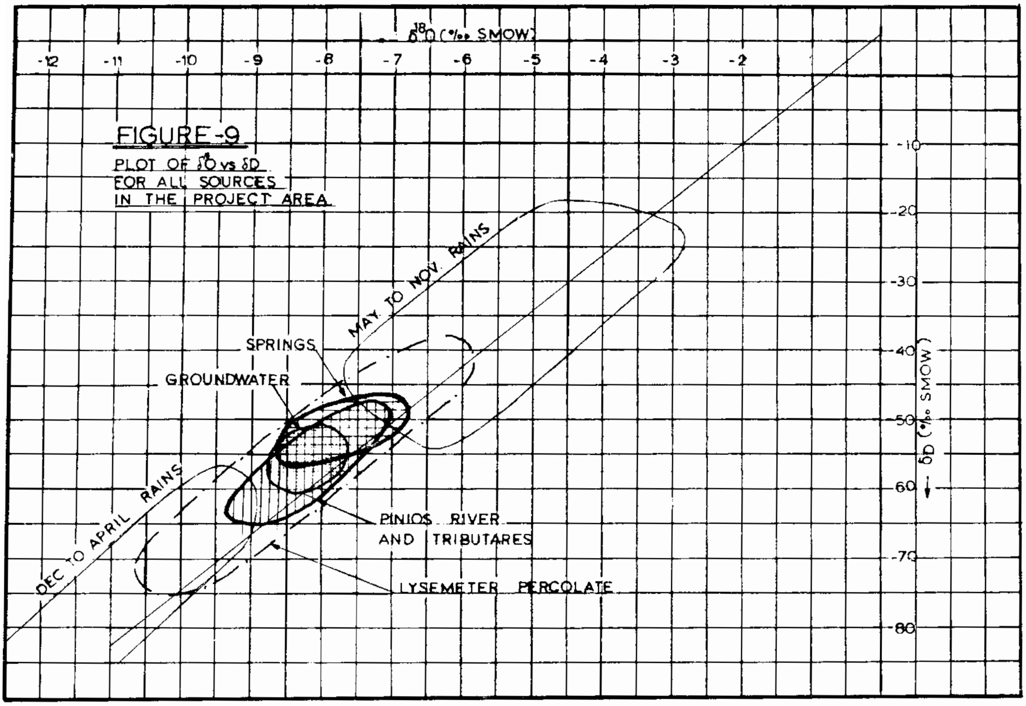


FIGURE-9

PLOT OF $\delta^{18}O$ vs δD FOR ALL SOURCES IN THE PROJECT AREA sources or that these might all be contributing in various proportions. However, for the rather shallow aquifer in the valley and particularly in the northern part of the valley where the valley fill is quite permeable coarse-grained material, it is most probable that the main sources of recharge are the river contribution to aquifers and the direct surface recharge. Thus, the $\delta^{18}O$ values observed in wells on the northern part ($-9.0\,^0/_{00}$ for D-3, $-8.7\,^0/_{00}$ for D-1, $-8.9\,^0/_{00}$ for D-2, $-8.7\,^0/_{00}$ for D-4 and $-8.6\,^0/_{00}$ for D-5) would be evidence of a major contribution of River Pinios ($\delta^{18}O = -9.2\,^0/_{00}$) to the aquifers. Similar considerations apply to the wells between the Pamissos and Portaikos Rivers and further to the east around the confluence of the Pamissos and Pinios Rivers. A probable interpretation of the relatively enriched values observed for D-22 ($\delta^{18}O = -7.7\,^0/_{00}$) and G-401 ($\delta^{18}O = -7.5\,^0/_{00}$) would be the contribution from direct recharge (or the samples might represent the upper layers of the aquifer where recent direct recharge occurred).

Significantly depleted $\delta^{18}O$ values observed in the south-eastern wells (from $-9.0\,^0/_{00}$ to $-10.3\,^0/_{00}$) as can be seen in Fig. 1 and Map 2, would be evidence of a recharge mechanism to the aquifer which is different to that of the western and northern part. Such depleted values can be due to its recharge area being located at very high altitudes, say higher than 1000 m. However, considering that the water in this part of the aquifer is very old (older than 30.000 years, as will be discussed in the next chapter), one should also consider this to be the result of possible changes in the paleoclimate of the area.

4. 3. 3. Tritium and ^{14}C results from springs and wells - Interpretations and evaluations.

4. 3. 3. 1. Qualitative Interpretations.

The tritium samples collected from wells enabled the study of the dynamics of the groundwater system in the Thessaly Valley. The tritium concentration of rainfall as observed at two precipitation stations and at four lysimeter stations is shown in Fig. 4, together with those observed in rivers, thus defining the range of tritium input into the system during the last three years.

The high tritium content observed in the springs and wells located in the western and northern part, certainly indicates that the aquifers are very active and that the transit time involved in groundwater is short (Wels D-1, D-2, D-3, D-4, D-5, and all the springs in the western and northern part). Comparatively lower tritium contents observed in wells located in the central part of the valley (D-16, D-12, D-13, D-15) indicate that the movement of water in this part is relatively slow and this is generally in agreement with aquifers being composed of finer material which is less permeable as compared to the northern part of the valley. Further to the east and in the south-eastern part of the project area, all wells are tritium-free and the ^{14}C data indicate the water to be at least 30.000 years old. Thus, the movement of water in the aquifers in the southeastern part must be very slow and recharge to the aquifer should be at a very low rate.

Corrected ^{14}C ages of the water for those wells where ^{14}C and ^{13}C analyses are available, are shown on Table 2. In correcting theages it is assumed that biogenic $\delta^{13}C$ is —25 ⁰/₀₀ which is a generally accepted value.

TABLE 2.

Well No	^{14}C (⁰/₀ Mod.)	$\delta^{13}C$ (⁰/₀₀)	Corrected Age (years)
D - 12	58.6	— 13.0	Recent
D - 13	41.1	— 13.9	2500
D - 15	41.1	— 15.6	3450
D - 17	66.0	— 11.3	Recent
D - 10	87.8	— 12.2	Recent
G - 407	0.7	— 16.0	More than 40.000
G - 408	0.2	— 10.4	More than 40.000
G - 409	1.1	— 5.8	25.200
G - 505	0.9	— 9.9	31.200

As can be seen from Table 2, the groundwaters tapped by wells D - 12, D - 17 and D - 10 are recent young waters, which are at relatively shallow depths as compared to others. Of particular interest is the age of water in wells D - 12, D - 13, D - 15, which are located very near to each other. Recent water observed in D - 12 which taps the upper horizons of the aquifer is evidence of the aquifer being more active as compared to the lower water-bearing horizons where the age of the water is about 2.500 - 3.500 years. Under the assumption that wells (D - 10) and (D - 13, D - 15) tap the same aquifer, the observed age gradient would indicate the average flow to be at a rate of about 5 m/year in this part of the valley.

Quantitative evaluations based on the tritium values of the springs and wells in the western and northern part of the area are given in the following paragraphs.

4. 3. 3. 2. **Quantitative Evaluations.**

Various conceptual simulation models are available to study the dynamics of a given storage element with tracers [**6**]. The methodical formulation of such conceptual simulation models generally requires that the time dependent tracer input function be determined and a certain transit time distribution function be adopted for the system under consideration, so that the tracer output can be computed and the comparison of the available actual measurements of the tracer content could enable the determination of the hydrodynamic characteristics of the system. Thus, in this respect the problem is typical of the «Prediction» type where «input» and «system response» (transit time distribution of the trace element) are known and the computed output serves as a means of studying the dynamics of the system by determining certain parameters that give the best fitting output to the actually observed output. Another possible evaluation with tracer data is, that known input and observed output from a given system can be used to determine the «system response function» (that is transit time distribution function), the knowledge of which would again enable the determination of certain hydrodynamic characteristics of the system under consideration which is a problem of the «Identification» type. However, this would require a long period of observation on the output for the evaluations to be possible and meaningful. Considering the fact that the available isotope data in the project area cover a very short period of time, the first approach has to be adopted which would require knowledge of the transit time distribution of the trace element in the system considered. In the case of groundwater flow and in groundwater storage elements, it is rather difficult to define the transit time distribution of the trace element since the dispersion and mixing occurring during the groundwater flow makes the whole process too complex for a full mathematical formulation. Thus, certain simplifying assumptions are inevitable for the mathematical formulation of the problem to result in practically satisfactory workable equations. The formulation adopted here is the one which assumes that the dispersion of traces in groundwater flow can be conceptually simulated by considering a cascade of reservoirs, each being a linear reservoir. Thus, each storage is proportional to outflow, that is,

$$V = K \cdot Q$$

K being the proportionality constant which has a unit of «Time». Thus, for each storage element, «K» is the so-far called «Mean Residence Time». For the case of a cascade of reservoirs composed of «n» reservoirs in series, each having the same K value, the residence time of the system as a whole will be **n** x K. For such a cascade of reservoirs, the system response function (transit time distribution function) will be [**7**]

$$\boxed{f_T(T) = \frac{1}{K}\,\frac{(t/K)^{n-1}\cdot e^{-t/K}}{(n-1)!}}$$

Thus, knowing the input to the system and using the above system response function, the output from the system can be computed by using the convolution integral of

$$C(t) = \int_0^{\infty} f_i(t - T)\cdot f_T(T)\cdot dT$$

since the system is a linear one. This would further require the assumption that the system is in a steady state contition (that is Inflow = Outflow = Constant).

The mathematical model adopted in this way for the conceptual simulation of tracer behaviour in groundwater flow is a two-parameter model which enables the determination on the mean residence time of flow (K) and the number of storage units (n) which is related to the hydrodynamic dispersion characteristics of the system. In view of the very short period of observation available in the project area, a number of storage elements to be used had to be selected arbitrarily and a cascade of reservoirs consisting of two storage units will be used in the computations.

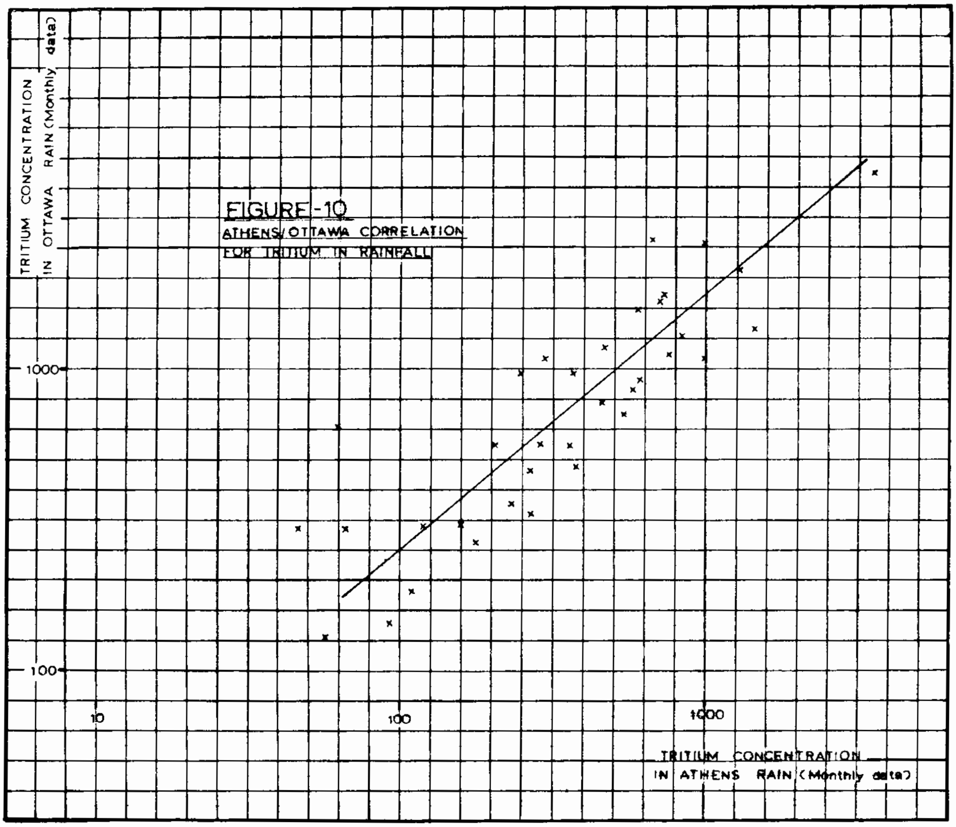
Since the tracer used in the evaluations will be tritium, a decay correction has to be introduced in the above equation,

thus $f_i(t - T)$ is the tritium input function

$f_T(T)$ is the transit time distribution function as defined earlier.

The computed tritium output curves for the project area, by using the above given equations, are shown on Fig. 11. The computations were carried out on a WANG - 700 computer. The computer programme developed for this purpose includes the necessary steps for a decay correction to be made automatically by the computer during the computations.

Some of the computed tritium output curves of Fig. 11 are based on quarterly data. The tritium input to the project area had to be estimated. Considering the tritium concentrations of rainfall as measured at the stations in the project area, for the last four years (1968 to 1971), the tritium concentration is assumed to be the same for each year and quarterly tritium concentrations are assumed to be 150, 250, 100 and 70 T. U. for the first, second, third and fourth quarter period, respectively. Tritium concentrations for quarterly periods of earlier years are estimated from available data of Athens, which is one of the WMO/IAEA network stations and also from an Ottawa/Athens correlation, which is shown on Fig. 10. The tritium concentration curve adopted for the evaluations is shown on Fig. 11. It should be pointed out that the tritium concentration curve shown on Fig. 11 should be corrected by the amount of rainfall to represent the tritium input function which could easily be done by computing the weighted mean values for each quarter. Fig. 12 shows the computed tritium output curves on an enlarged scale for various mean residence times $\left(\frac{\text{volume}}{\text{inflow}} = \frac{\text{volume}}{\text{outflow}} = K\right)$ values for the last five years. The observed tritium values from selected springs and wells are also shown on Fig. 12.



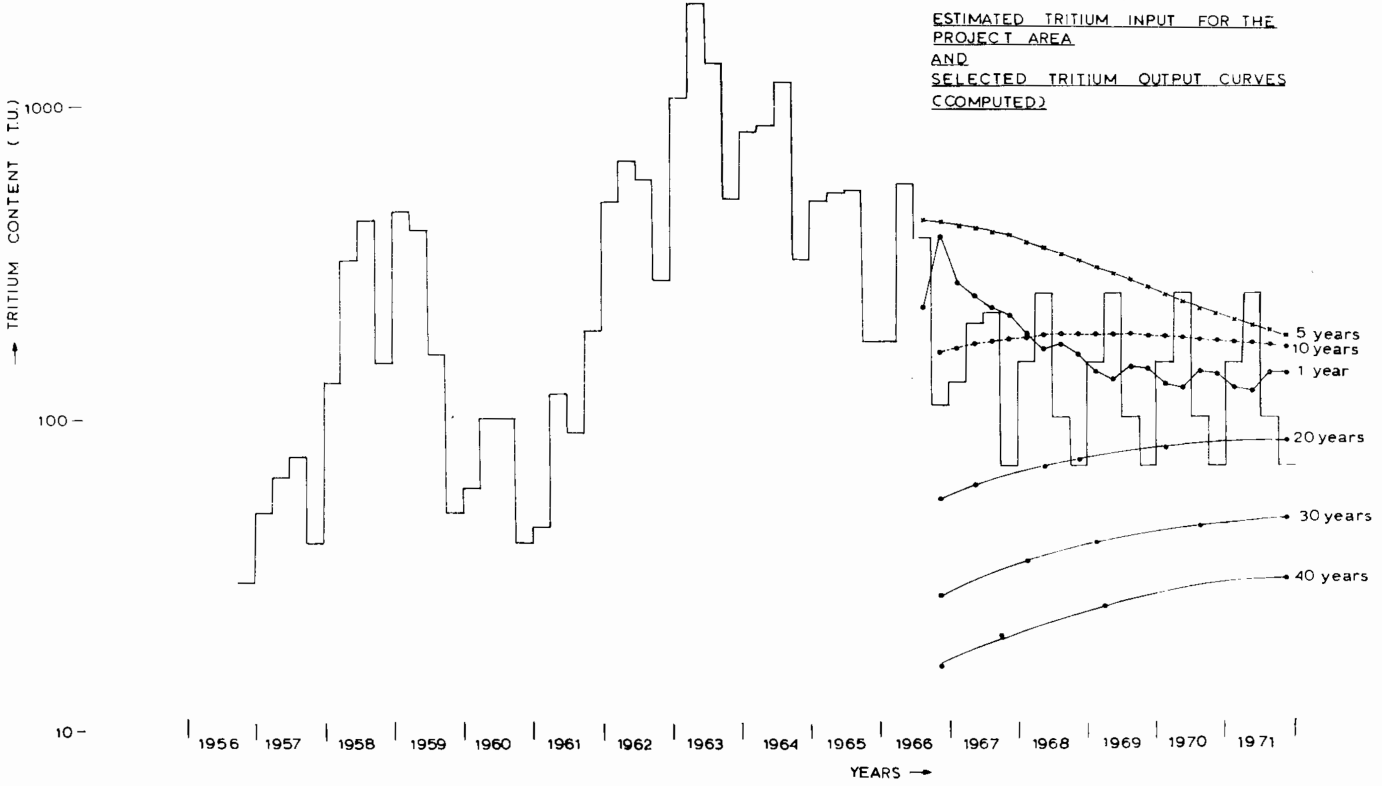


FIGURE - 11

ESTIMATED TRITIUM INPUT FOR THE PROJECT AREA AND SELECTED TRITIUM OUTPUT CURVES (COMPUTED)

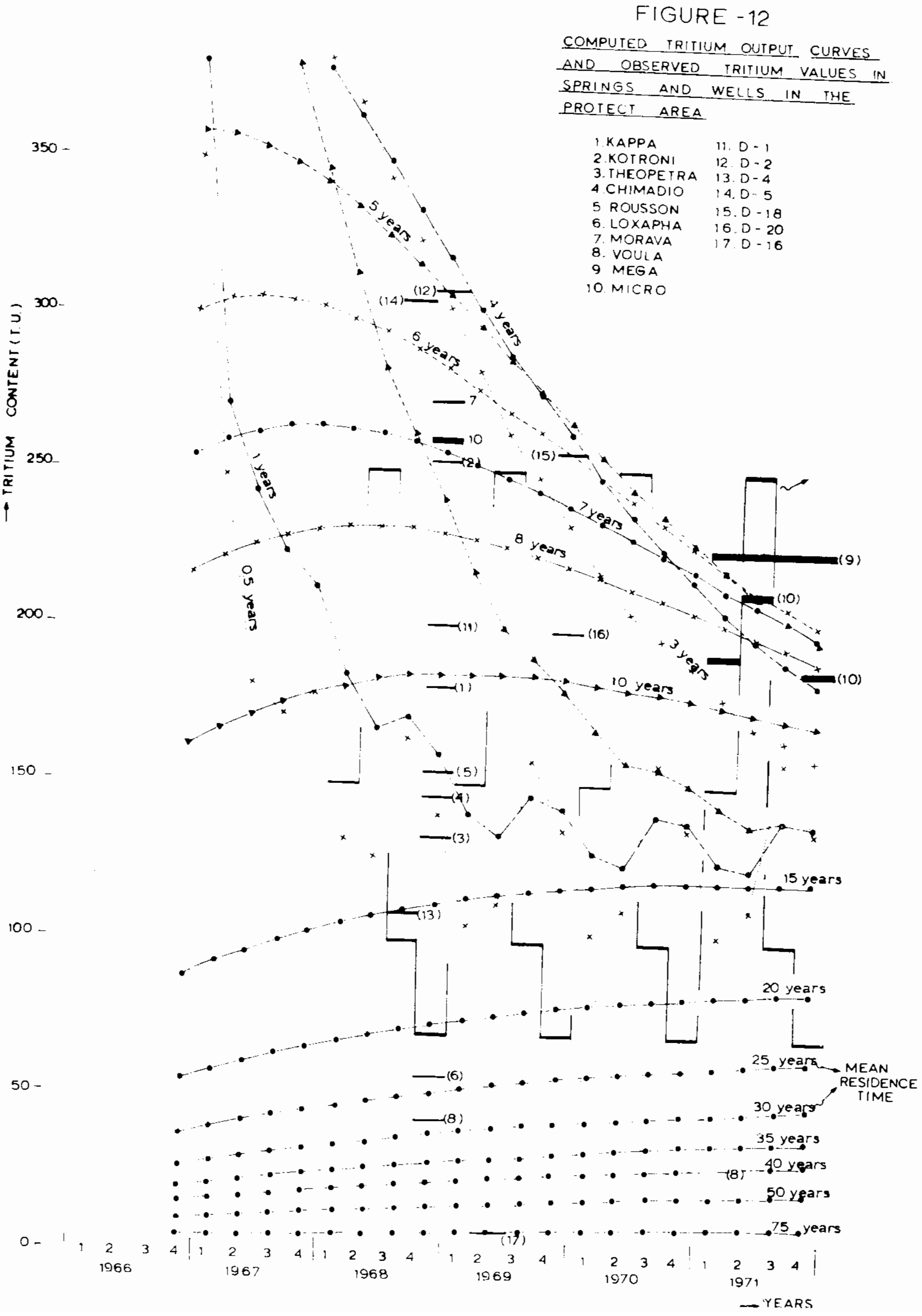


FIGURE -12

COMPUTED TRITIUM OUTPUT CURVES AND OBSERVED TRITIUM VALUES IN SPRINGS AND WELLS IN THE PROTECT AREA

Thus, comparison of the observed tritium output curves enables the determination of mean residence times for springs and groundwater in the valley. Since the tritium input function used represents the rainfall input, the computed output curves of Fig. 12 should be used for tritium values observed in the flow system where the recharge is directly from rainfall. Thus, observed tritium values shown on Fig. 12 are for those springs where their location and stable isotopes suggest that recharge occurs from rain falling on surrounding highlands. The use of Fig. 12 for evaluations of tritium data observed in the wells also requires that the recharge of groundwater is mainly from the rain falling either on the alluvium valley or on the surrounding mountains.

As can be seen from Fig. 12, the mean residence time of flow for Kotroni and Morava Springs should be either 2 - 3 years or about 6 - 7 years. It is evident that a more accurate evaluation of the mean residence time, by using Fig. 12, would require a number of observations on the output covering a reasonable period of time rather than a single measurement as is generally the case in the project area. A longer observation of tritium in these springs, for example would enable a selection between the two possible ranges of values. Similar considerations apply to all sampled sources where there are only one or a few tritium measurements available.

The tritium values observed in Kappa, Theopetra, Chimadio and Rousson Springs indicate that the mean residence time of flow for these springs should be either 0.5 - 1 year or 10 to 15 years. Spring Loxadha with an observed tritium content of 57 T. U. should have a mean residence time of about 25 years. It should also be considered that the tritium value observed can also be evidence for a rapid response (less than, say, six months) to the input since the rain tritium concentration prior to the sampling months is about 70 T. U. Thus, as mentioned earlier, a selection between these two possible answers could only be made if a series of measurements were available. The tritium values observed in Voula Spring at two different samplings indicate that it has a mean residence time of about 30 - 40 years.

Tritium measurements available from Micro-Kephalovrisson Spring indicate that the mean residence time of flow is about 6 - 8 years for this spring, should the recharge to the spring be from the rain falling on the alluvium valley or from the rain falling on the northern mountains. As already mentioned in earlier chapters, the stable isotope data suggest that recharge to the springs in the central part of the valley occurs partly from the rivers. Thus, the above mean residence time given for this spring should be considered as a rough estimate since the tritium input from the rivers is not taken into account in the evaluations.

In the case of a river water contribution as one of the recharge components, one should try to evaluate the tritium output curves by using a two-component flow system, where one of the components is river and the other is direct recharge. This would require the knowledge of the tritium content of the Pinios River for longer periods of time, which is not available. However, considering that the tritium content of a river draining rather small catchment areas should, on the average, be close to that of rainfall over the catchment area with less fluctuations, as also suggested by the available tritium data, the above mean residence time can still be considered as a rough estimate for Micro Kephalovrisson Spring, even if the Pinios River contribution to the spring flow is valid.

Tritium values observed in Mega - Kephalovrisson Spring are quite uniform and a rough estimate of the mean residence time for this spring would be about 4 - 7 years. However, one should also consider the fact that the rather uniform tritium values observed in the spring compared to those of Pinios River, might suggest an even shorter residence time for the spring water being mainly recharged from the Pinios River.

The mean residence times evaluated for the springs in this way are useful since they provide information on the time involved in groundwater flow and have additional significance in that they enable further evaluations to be made as regards the groundwater system. Recalling the fact that the mean residence time is equivalent to the $\frac{\text{Volume}}{\text{Outflow}}$ or $\frac{\text{Volume}}{\text{Inflow}}$ ratio of the system, a knowledge of outflows from the springs would enable the estimation of their respective reservoir volumes which is certainly a good information in the study of available water resources. For example, if lower values of the mean residence times given above are used for each spring and, knowing the mean discharges of the springs, estimates of their respective storage volumes can be made. Table 3 illustrates this and gives the estimated storage volumes for some springs.

It should be pointed out that the above estimates of storage volume are based on the lower values of the mean residence time and thus reflect minimum storage values in that respect.

Tritium values observed in the wells can be used in a similar manner to estimate the mean residence time involved in the flow of groundwater in aquifers of the valley.

The tritium values observed in the northern part of the valley (Kalambaka Basin) (Wells D - 1, D - 2, D - 4, D - 5) indicate the mean residence time of flow to be about 4 - 15, years in this part of the valley. Similarly, the tritium values of wells D - 18 and D - 20 would indicate a mean residence time of about 4 - 10 years for the aquifer tapped by

TABLE 3.

Name of Spring	Estimated Mean Residence Time (Years)	Mean Annual Discharge (m^3)	Estimated Reservoir Volume (m^3)
Kappa	1	1750	1750
Theopetra	1	2600	2600
Chimadio	1	2000	2000
Morava	2	9.5×10^6	19×10^6
Voula	30	12.5×10^6	3.75×10^8
Micro-Kephalovrisson	6	12.5×10^6	7.5×10^7
Mega-Kephalovrisson	4	8.5×10^6	3.4×10^7

these wells. The quite low tritium values observed in the wells located in the central part of the valley are evidence for the rather slow movement and would indicate the mean residence time of flow to be at least 75 years.

5. CONCLUSIONS

The environmental isotope study carried out in the Western Thessaly Valley has enabled interpretations and evaluations to be made as regards the source of recharge and recharge mechanism in the flow system of the valley and also provided useful information on the dynamics of the flow system.

1. The stable isotope data available from the project area indicate that recharge to the groundwater in the Kalambaka Basin occurs most probably both from the Pinios River (and its tributaries) and from rainfall as direct recharge. Estimates based on the available isotope data would result at about 60% river contribution and 40% direct recharge.

2. The groundwater in the south-eastern part of the area has a significantly different stable isotope content from that in the western and northern part and the recharge mechanism in this part must be different.

3. The stable isotope data of the springs located in the mountaneous region and at the foothills enables the determination of the altitude of their respective recharge areas and this is generally higher than 500 - 600 meters.

Springs Micro-Kephalovrisson and Mega-Kephalovrisson, which are of particular interest, are most probably being recharged by the Pinios River and, partly, by the rainfall occurring on the alluvium plain.

4. The tritium and ^{14}C data available indicate that, in the northern and western part of the valley, where aquifers are mainly composed of coarse material, the movement of water is rather rapid and the aquifers are quite active. The mean residence time of flow is about 4 - 15 years in this part of the valley.

5. In the central part of the valley, where aquifers are confined and overlain by less permeable, fine, younger sediments, the movement of water is relatively slow and the tritium data indicate the mean residence time to be at least 75 years. Estimates based on ^{14}C ages would indicate the average flow rate to be about 5 m/year in the central part of the aquifer.

6. The very old water in the south - eastern part of the area indicates that the movement of water is very low and, thus, recharge to the aquifer must be at a very low rate.

7. The tritium values available from the springs enabled estimates of the mean residence time of flow and also their respective storage volumes. Springs Micro - Kephalovrisson and Mega - Kephalovrisson have a mean residence time of about 4 - 7 years.

Along with the above summarized findings, the report aims at presenting methodologies involved in the evaluation and interpretation of environmental isotope data to yield hydrogeological information as regards the flow system and its dynamics.

ΠΕΡΙΛΗΨΙΣ

1. ΓΕΝΙΚΑ

Ἐντὸς τῶν πλαισίων τῆς ὑπὸ τοῦ τ. Ι.Γ.Ε.Υ. ἐκτελεσθείσης ἐρεύνης ἐπὶ τοῦ δυναμικοῦ τῶν ὑπογείων ὑδάτων Θεσσαλίας (1964 - 1972), ἐξετελέσθη τὸ 1968 ἰσοτοπικὴ ὑδρολογικὴ ἔρευνα, ἐν συνεργασίᾳ, ὑπὸ τοῦ Δ.Ο.Α.Ε., τοῦ Κ.Π.Ε. «ΔΗΜΟΚΡΙΤΟΣ» καὶ τοῦ τ. Ι. Γ. Ε. Υ. (νῦν Ι. Γ. Μ. Ε.) διὰ χρησιμοποιήσεως φυσικῶν ἰσοτόπων.

Ἡ κοιλὰς Δυτ. Θεσσαλίας συνιστᾷ μίαν μεγάλην πεδιάδα, διευθύνσεως ΒΔ-ΝΑ, μήκους 70 καὶ εὔρους 30 km, τῆς ὁποίας τὸ ὑψόμετρον κεῖται μεταξὺ 90 καὶ 120 μ.ὕ.θ. Ἡ πεδιὰς ἀποστραγγίζεται ὑπὸ τοῦ Πηνειοῦ ποταμοῦ, ῥέοντος ἐκ ΒΒΔ πρὸς ΝΝΑ καὶ ἐν συνεχείᾳ ἐκ Δ πρὸς Α καὶ τῶν παραποτάμων αὐτοῦ. Τὸ ἀνώτερον (ΒΔ/κὸν) τμῆμα τῆς Δυτικῆς Θεσσαλικῆς πεδιάδος, ἡ καλουμένη λεκάνη Καλαμπάκας, ἔχει μελετηθῆ καὶ περιγραφῆ ὑδρογεωλογικῶς ὑπὸ τοῦ Γ. Α. ΚΑΛΛΕΡΓΗ [**1**].

Τὰ πρὸς ἐπίλυσιν, διὰ τῆς χρησιμοποιήσεως ἰσοτόπων τεθέντα βασικὰ προβλήματα ἦσαν ἡ σχέσις μεταξὺ ἐλευθέρων καὶ ὑπὸ πίεσιν ὑδροφόρων ὁριζόντων, ἡ τροφοδοσία τούτων καί, εἰ δυνατόν, ἡ ταχύτης ροῆς τοῦ ὑπογείου ὕδατος. Ἡ παροῦσα ἐργασία παρουσιάζει τὰ ἰσοτοπικὰ δεδομένα, ἅτινα ἐλήφθησαν κατὰ τὴν ἐκτέλεσιν τῆς ἐρεύνης, καὶ τὴν ἑρμηνείαν τούτων.

2. ΓΕΩΛΟΓΙΚΑΙ ΚΑΙ ΥΔΡΟΓΕΩΛΟΓΙΚΑΙ ΣΥΝΘΗΚΑΙ ΤΗΣ ΠΕΡΙΟΧΗΣ

2. 1. Γεωλογικαὶ συνθῆκαι.

Ἡ κοιλὰς Δυτ. Θεσσαλίας ἀποτελεῖ τμῆμα τῆς «Μεσοελληνικῆς αὔλακος», ἥτις ἐδημιουργήθη ἐκ τῶν τεκτονικῶν γεγονότων, τὰ ὁποῖα ἔλαβον χώραν μετὰ τὴν κυρίαν τεκτονικὴν φάσιν (μέσον - ἀνώτερον Ἠώκαινον) κατὰ τὸ στάδιον τῆς χαλαρώσεως.

Ἡ αὖλαξ αὕτη ἐσχηματίσθη μεταξὺ τῆς πινδικῆς κορδιλλιέρας — ἀπαρτιζομένης ἐξ ἰζηματογενῶν πετρωμάτων τριαδικῆς ἕως ἠωκαινικῆς ἡλικίας τοῦ πινδικοῦ γεωσυγκλίνου — ἡ ὁποία εἶχεν ἀναδυθῆ ἐξ ὁλοκλήρου κατὰ τὸ μέσον Ἠώκαινον καὶ τῆς ὑποπελαγονικῆς καὶ πελαγονικῆς κορδιλλιέρας, αἵτινες εἶχον ἀναδυθῆ ἀντιστοίχως κατὰ τὸ Ἠώκαινον καὶ Μαιστρίχτιον. Ἡ ὑποπελαγονικὴ ζώνη, ἀναπτυσσομένη μεταξὺ τοῦ πινδικοῦ γεωσυγκλίνου καὶ τῆς πελαγονικῆς ράχεως, περιλαμβάνει ἰζήματα ἐνδιάμεσα μεταξὺ τῆς πελαγικῆς καὶ ὑφαλογόνου φάσεως, καθὼς καὶ ὀφιολιθικὰς ἐκχύσεις. Ἡ ἡλικία τῶν σχηματισμῶν τῆς ὑποπελαγονικῆς ζώνης εἶναι τριαδικὴ ἕως καὶ ἠώκαινος. Τέλος ἡ πελαγονικὴ ζώνη περιλαμβάνει ἰζήματα ὑφαλογόνου φάσεως νεοπαλαιοζωϊκῆς (;) ἕως μαιστριχτίου ἡλικίας, ἅτινα ἔχουν ὑποστῆ μεταμόρφωσιν.

Τὸ ὑπόβαθρον τῶν ἀποθέσεων τοῦ πληρώματος τῆς αὔλακος, ἀλλὰ καὶ τὰ κράσπεδα ταύτης συνίστανται ἐκ πετρωμάτων τῶν ὡς ἄνω τριῶν ζωνῶν. Τὰ πετρώματα τῶν πινδικῆς καὶ ὑποπελαγονικῆς ζωνῶν (ἀνθρακικὰ πετρώματα - σχιστοκερατόλιθοι - ὀφιόλιθοι - φλύσχης) ἀναπτύσσονται κυρίως εἰς τὰ ΒΒΔ/κά, Δυτικὰ καὶ Νότια κράσπεδα τῆς κοιλάδος, ἐνῷ τὰ πετρώματα τῆς Πελαγονικῆς ζώνης (μάρμαρα - κρυσταλλικοὶ σχιστόλιθοι, γνεύσιοι κλπ.) ἀναπτύσσονται εἰς τὰ ΒΑ/κὰ καὶ Ἀνατολικὰ κράσπεδα τῆς κοιλάδος.

Μεταξὺ τῶν ἐν λόγῳ πετρωμάτων, ἅτινα ἀποτελοῦν καὶ τὸν πυθμένα της, διηνοίχθη ἡ «Μεσοελληνικὴ αὖλαξ», ἡ ὁποία ἐπληρώθη ὑπὸ σχηματισμῶν ἠωκαινικῆς ἕως καὶ βουρδιγαλίου ἡλικίας, ἄλλοτε μὲν θαλασσίας, ἄλλοτε δὲ χερσαίας ἢ ποταμίου φάσεως, συνολικοῦ πάχους ὑπὲρ τὰ 1.500 μέτρα. Οἱ ἐν λόγῳ σχηματισμοὶ περιλαμβάνουν ὀργανογενεῖς ἀσβεστολίθους, μάργας κροκαλοπαγῆ καὶ ψαμμίτας.

Μετὰ τὴν πλήρωσιν τῆς αὔλακος ὑπὸ τῶν ἀνωτέρω πετρωμάτων (Βουρδιγάλιον), ἐντὸς ταύτης ἤρχισεν ἡ ἀπόθεσις χερσαίων ἢ ποταμοχειμαρρωδῶν ὑλικῶν, ἅτινα ἐδημιούργησαν μίαν παχεῖαν σειρὰν πλειοπλειστοκαινικοῦ - ὁλοκαινικοῦ συνάγματος (κροκάλαι - ἄμμοι διαφόρου κοκκομετρίας, ἰλεῖς καὶ ἄργιλοι εἰς ποικίλα ἑκάστοτε ποσοστὰ ἀναμίξεως). Τὸ ἐν λόγῳ σύναγμα εἶναι ἁδρομερὲς εἰς τὰ κράσπεδα τῆς λεκάνης (κῶνοι τοῦ Πηνειοῦ καὶ τῶν παραποτάμων αὐτοῦ), ἔνθα ἐπικρατοῦν αἱ κροκάλαι, λατύπαι καὶ χονδρόκοκκοι ἄμμοι, καθιστάμενον λεπτομερέστερον καθ' ὅσον βαίνομεν πρὸς τὸ κέντρον αὐτῆς (ἰλεῖς, ἄργιλοι ἐναλλασσόμεναι πρὸς μεσοκόκκους ἕως λεπτοκόκκους ἄμμους). Ἐντὸς τῶν ἐν λόγῳ πλειοπλειστοκαινικῶν - ὁλοκαινικῶν σχηματισμῶν ἀναπτύσσονται σημαντικοὶ ὑδροφόροι ὁρίζοντες.

2. 2. **Ὑδρογεωλογικαὶ συνθῆκαι.**

Ὁλόκληρον τὸ πεδινὸν τμῆμα τῆς κοιλάδος τῆς Δυτικῆς Θεσσαλίας καταλαμβάνεται ἐκ τῶν ποταμοχειμαρρωδῶν πλειοπλειστοκαινικῶν - ὁλοκαινικῶν ὑλικῶν, τῶν ὁποίων ἡ κοκκομετρία βαίνει ἐλαττουμένη ἐκ Β πρὸς Ν καὶ ἐκ Δ πρὸς Α. Οἱ κῶνοι τοῦ Πηνειοῦ καὶ τῶν παραποτάμων αὐτοῦ (Πορταϊκὸς - Πάμισσος - Σοφαδίτης - Ἐνιπεὺς) συνίστανται ἐξ ἁδρομεροῦς συνάγματος μὴ παρουσιάζοντος σημαντικὰς κοκκομετρικὰς μεταβολὰς κατὰ τὴν κατακόρυφον. Ἐνταῦθα ἀναπτύσσονται σημαντικοὶ ἐλεύθεροι ὑδροφόροι ὁρίζοντες. Πρὸς τὸ κέντρον ὅμως τῆς λεκάνης παρατηρεῖται μεταβολὴ τῆς κοκκομετρίας ὄχι μόνον κατὰ τὴν ὁριζόντιον, ἀλλὰ καὶ κατὰ τὴν κατακόρυφον, μὲ ἀποτέλεσμα νὰ δημιουργοῦνται ἐπάλληλα στρώματα ἁδρομερεστέρων (ἄμμος μεσόκοκκος - λεπτόκοκκος) καὶ λεπτομερεστέρων (ἰλεῖς - ἄργιλοι) ὑλικῶν. Τοῦτο συνεπάγεται ἀνάπτυξιν ἑνὸς ἐπικρεμαμένου πτωχοῦ ἐλευθέρου ὑδροφόρου ὁρίζοντος καὶ ἐπαλλήλων ὑπὸ πίεσιν ὑδροφόρων ὁριζόντων συνδεομένων ὑδραυλικῶς μετὰ τῶν ἐλευθέρων ὑδροφόρων ὁριζόντων τῶν κώνων τοῦ Πηνειοῦ καὶ τῶν παραποτάμων αὐτοῦ. Χαρακτηριστικὸν εἶναι, ὅτι εἰς τὰ ὅρια ἔνθα ὁ ἐλεύθερος ὑδροφόρος ὁρίζων τοῦ κώνου τοῦ Πηνειοῦ μεταπίπτει εἰς ἐπαλλήλους ὑδροφόρους ὁρίζοντας ὑπὸ πίεσιν, ἐμφανίζονται πηγαὶ (πηγαὶ Μικροῦ καὶ Μεγάλου Κεφαλόβρυσου). Ἐντὸς τῆς πεδιάδος ὑφίστανται καὶ ἄλλαι πηγαῖαι ἐκδηλώσεις (ἀλλουβιακαὶ πηγαὶ Πουλιάνας, Γηλάνθης κλπ.).

Μία σειρὰ καρστικῶν πηγῶν συναντᾶται ἐπίσης εἰς τὰ κράσπεδα τῆς κοιλάδος (καρστικαὶ πηγαὶ Διάβας, Μοράβας, Βούλας, Κλοκωτοῦ, Πύλης, Μουζακίου κλπ.).

3. ΓΕΝΙΚΑΙ ΑΡΧΑΙ ΕΠΙ ΤΗΣ ΕΦΑΡΜΟΓΗΣ ΤΩΝ ΦΥΣΙΚΩΝ ΙΣΟΤΟΠΩΝ ΤΟΥ ΠΕΡΙΒΑΛΛΟΝΤΟΣ

Τὰ συνήθως χρησιμοποιούμενα [**2**, **3**, **8**] φυσικὰ ἰσότοπα τοῦ περιβάλλοντος εἶναι τὰ σταθερὰ ἰσότοπα Δευτέριον καὶ Ὀξυγόνον - 18, ὡς καὶ τὰ ραδιενεργὰ Τρίτιον καὶ Ἄνθραξ - 14. Τὰ πρῶτα τρία ἰσότοπα ἀπαντοῦν εἰς τὸ μόριον τοῦ ὕδατος καὶ ὡς ἰσοτοπικοὶ ἰχνηθέται συνιστοῦν τοὺς μόνους πραγματικοὺς ὑδατικοὺς ἰχνηθέτας, τοὺς ὁποίους διαθέτει ὁ ὑδρογεωλόγος. Ὅλοι οἱ ἄλλοι ὑδάτινοι ἰχνηθέται ἀπαντοῦν ἐν διαλύσει καὶ ὡς ἐκ τούτου ὑπόκεινται εἰς ἀπωλείας, λόγῳ καθιζήσεως, προσροφήσεως καὶ ἀνταλλαγῆς.

Εἰς τὰ προαναφερθέντα ἰσότοπα δέον ὅπως προστεθῇ ὁ ἄνθραξ - 13, ὅστις χρησιμοποιούμενος ἐν συνδυασμῷ μὲ τὸν ἄνθρακα - 14 καὶ γεωχημικὰ δεδομένα, δυνατὸν συχνὰ νὰ ἐπαυξήσῃ τὴν ἀκρίβειαν τῆς «ραδιοχρονολογήσεως», τῆς λαμβανομένης ἐκ τοῦ ἄνθρακος - 14.

3. 1. Ὀξυγόνον - 18 καὶ Δευτέριον.

Αἱ μεταβολαὶ τῶν σταθερῶν ἰσοτόπων ὑδρογόνου καὶ ὀξυγόνου, αἱ παρατηρούμεναι εἰς τὰ φυσικὰ ὕδατα, συχνὰ δίδουν στοιχεῖα, ἐπὶ τῆς προελεύσεως τούτων [**3, 4, 5, 8**]. Γενικῶς αἱ μεταβολαί, εἰς τὴν περιεκτικότητα σταθερῶν ἰσοτόπων, εἰς κατὰ τὸ μᾶλλον ἢ ἧττον σύγχρονα ὑπόγεια ὕδατα, συνδέονται:

1) μὲ διαφορὰς εἰς τὴν θερμοκρασίαν συμπυκνώσεως καί, κατὰ συνέπειαν, συχνὰ μὲ μεταβολὰς εἰς τὸ ὑψόμετρον τῆς περιοχῆς, ἐκ τῆς ὁποίας τροφοδοτοῦνται τὰ ὑπόγεια ὕδατα ἐκ τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων καὶ

2) μὲ τὴν ἀπόστασιν τῆς περιοχῆς ἐκ τῶν ὠκεανίων πηγῶν ὑγρασίας. Ἐν τούτοις τοιαῦται διαφοραὶ εἰς τὴν ἰσοτοπικὴν σύνθεσιν παλαιῶν (παλαιοτέρων ἀπὸ μερικὰς χιλιάδας ἐτῶν) ὑδάτων δυνατὸν νὰ ὀφείλωνται εἰς παλαιοκλιματικὰς διαφορὰς (μεταβολαὶ θερμοκρασίας καὶ ὑγρασίας συνδεόμεναι μὲ τὴν τελευταίαν παγετώδη περίοδον).

Ἐπίσης, τροφοδοσία ἐξ ἐπιφανειακῶν ὑδάτων (ποταμοὶ - λίμναι - ἕλη), εἰς τὰ ὁποῖαι λαμβάνει χώραν ἐκλεκτικὴ ἐξάτμισις τῶν ἐλαφρῶν ἰσοτόπων (^{16}O καὶ ^{1}H), προκαλεῖ ἐμπλουτισμὸν τῶν ὑπογείων ὑδάτων εἰς βαρέα ἰσότοπα (^{18}O καὶ D), ἤτοι προσδίδει εἰς αὐτὰ θετικὰς ἢ ὀλίγον ἀρνητικὰς ἀποκλίσεις ἀπὸ τὸ πρότυπον SMOW [1].

3. 2. Τρίτιον.

Τὸ ἐν λόγῳ ἰσότοπον παρέχει χρησίμους πληροφορίας περὶ τῆς ἡλικίας, ἤτοι τοῦ πιθανοῦ χρόνου τροφοδοσίας τοῦ ὑπογείου ὕδατος, ἐφ' ὅσον τοῦτο εἶναι νεώτερον ἀπὸ 30 - 40 χρόνια. Ἡ ὑπὸ τοῦ Τριτίου ὑποδεικνυομένη ἡλικία τοῦ ὑπογείου ὕδατος ἀντιστοιχεῖ εἰς τὸν διαδραμόντα χρόνον μεταξὺ τῆς κατεισδύσεως τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων εἰς τὴν ἀκόρεστον ζώνην καὶ τῆς στιγμῆς τῆς δειγματοληψίας. Ἡ τοιαύτη ὅμως ἡλικία εἶναι ἐνδεικτικὴ μόνον. Ἡ προέλευσις τοῦ Τριτίου τῆς ἀτμοσφαίρας εἶναι εἴτε κοσμικὴ (κοσμικὴ ἀκτινοβολία), ἀνερχομένη εἰς συγκέντρωσιν 10 T. U. [2] εἰς τὰ ἀτμοσφαιρικὰ κατακρημνίσματα

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[1] Standard Mean Ocean Water.

[2] Tritium Units = Μονάδες Τριτίου. 1. T. U. = 1 ἄτομον Τριτίου ἀνὰ 10^{18} ἄτομα ὑδρογόνου.

εἰς παγκόσμιον κλίμακα, εἴτε θερμοπυρηνικὴ (δοκιμαὶ θερμοπυρηνικῶν ἐκρήξεων μεταξὺ 1952 καὶ 1963).

Εἰς τὴν Δυτικὴν Θεσσαλίαν αἱ συγκεντρώσεις Τριτίου τῶν ὑπογείων ὑδάτων ποικίλλουν ἀπὸ 0 ἕως 300 T. U. Γενικῶς εὑρέθη Τρίτιον εἰς τὸ ὕδωρ πηγῶν καὶ φρεάτων εὑρισκομένων πλησίον τῶν περιθωρίων τῆς λεκάνης, ἐνῷ εἰς τὸ ὕδωρ τῶν γεωτρήσεων τοῦ κεντρικοῦ τμήματος αὐτῆς δὲν εὑρέθη Τρίτιον. Αἱ μεταβολαὶ εἰς τὴν περιεκτικότητα Τριτίου εἰς τὰ διάφορα δείγματα ὕδατος δυνατὸν νὰ ὀφείλωνται εἰς :

α. Τοπικὰς μεταβολὰς εἰς τὴν ποιότητα τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων ἀπὸ ἔτους εἰς ἔτος.
β. Τοπικὰς μεταβολὰς τῆς κατεισδύσεως συνεπείᾳ διαφορῶν τοῦ ἐδάφους καὶ τῆς χλωρίδος.
γ. Τοπικὰς μεταβολὰς εἰς τὴν ὑδροπερατότητα καὶ τὸ πάχος τῆς ἀκορέστου ζώνης προκαλούσας μεταβολὰς εἰς τὸν ἀπαιτούμενον χρόνον, ἵνα ἡ ὑψηλὴ συγκέντρωσις Τριτίου ἐκ τῆς τελευταίας περιόδου θερμοπυρηνικῶν δοκιμῶν (1962 - 1964) φθάσῃ τὴν ἀκόρεστον ζώνην.

Διὰ λόγους εὐκολίας λαμβάνεται τὸ ἔτος 1953 ὡς ἀρχὴ τῆς ἐπιδράσεως τῶν θερμοπυρηνικῶν ἐκρήξεων εἰς τὴν συγκέντρωσιν Τριτίου εἰς τὴν ἀτμόσφαιραν.

Ὑπὸ τὰς προαναφερθείσας γενικεύσεις, διάφοροι συγκεντρώσεις Τριτίου δύναται νὰ συνδεθοῦν πρὸς τὴν μέσην ἡλικίαν τῶν δειγμάτων ὕδατος, ὡς ἀκολούθως :

α. 0 - 3 T. U. Ἡ μέση ἡλικία (ἀπὸ τῆς εἰσόδου εἰς τὴν ἀκόρεστον ζώνην) τοῦ ὕδατος κυμαίνεται μεταξὺ 15 καὶ 35 ἢ περισσοτέρων ἐτῶν (μεγαλυτέρα τῶν 35 ἐτῶν διὰ δείγματα ὕδατος, εἰς τὸ ὁποῖον δὲν εὑρέθη Τρίτιον).
β. 3 - 30 T. U. Ἡ τροφοδοσία (εἴσοδος τοῦ ὕδατος εἰς τὴν ἀκόρεστον ζώνην) ἔλαβε χώραν εἰς τὰ πρῶτα ἔτη τῆς περιόδου τῶν θερμοπυρηνικῶν δοκιμῶν.
γ. > 30 T. U. Ἡ τροφοδοσία ἔλαβε χώραν κατὰ τὰ τελευταῖα ἔτη τῆς περιόδου τῶν θερμοπυρηνικῶν δοκιμῶν ἢ μετὰ ταύτην.

3. 3. **Ἰσότοπα ἄνθρακος.**

Τὰ ἰσότοπα ἄνθρακος (Ἄνθραξ - 12, Ἄνθραξ - 13 καὶ Ἄνθραξ - 14) εἶναι χρήσιμα εἰς τὴν ὑδρογεωλογικὴν ἑρμηνείαν, κυρίως διότι ὁ Ἄνθραξ - 14 (ὅπως καὶ τὸ Τρίτιον) εἶναι ραδιενεργὸν ἰσότοπον, τοῦ ὁποίου ὁ χρόνος ὑποδιπλασιασμοῦ εἶναι 5.730 ἔτη καὶ οὕτω χρησιμοποιεῖται διὰ τὴν χρονολόγησιν ὑδάτων ἡλικίας μερικῶν χιλιάδων ἐτῶν.

4. ΑΠΟΤΕΛΕΣΜΑΤΑ ΤΗΣ ΕΡΕΥΝΗΣ ΔΙΑ ΧΡΗΣΙΜΟΠΟΙΗΣΕΩΣ ΦΥΣΙΚΩΝ ΙΣΟΤΟΠΩΝ - ΕΡΜΗΝΕΙΑ ΑΞΙΟΛΟΓΗΣΙΣ

4. 1. **Διαθέσιμα ἰσοτοπικὰ δεδομένα.**

Τὸ πρόγραμμα δειγματοληψίας, ἡ ὁποία ἐξετελέσθη εἰς τὴν κοιλάδα Δυτικῆς Θεσσαλίας, καλύπτει τὴν περίοδον Ὀκτωβρίου 1968 - Ἰουλίου 1971 καὶ περιέλαβεν ἐπιλεγέντας βροχομετρικοὺς σταθμούς, λυσίμετρα, ὑδατορρεύματα, πηγὰς καὶ γεωτρήσεις. Δείγματα, τὰ ὁποῖα ἐλήφθησαν εἰς διαφόρους περιόδους ἐκ τῶν ὡς ἄνω σημείων, ἀνελύθησαν διὰ φυσικὰ ἰσότοπα. Αἱ ἀναλύσεις ἐξετελέσθησαν εἰς τὸ Ἰσοτοπικὸν Ἐργαστήριον τοῦ ΔΟΑΕ εἰς Βιέννην, πλὴν τοῦ Δευτερίου, τοῦ ὁποίου αἱ ἀναλύσεις ἐγένοντο εἰς τὸ Γεωφυσικὸν Ἰσοτοπικὸν Ἐργαστήριον τοῦ Πανεπιστημίου τῆς Κοπεγχάγης.

Τὰ ἀποτελέσματα τῶν ἰσοτοπικῶν ἀναλύσεων τῶν ὑπογείων ὑδάτων (γεωτρήσεις - πηγαὶ) δίδονται εἰς τὸν πίνακα 4, ἐνῷ τῶν βροχομετρικῶν καὶ λυσιμετρικῶν σταθμῶν ὡς καὶ τῶν ὑδρορρευμάτων δίδονται εἰς τὸν πίνακα 5. Τὰ σημεῖα δειγματοληψίας ὁμοῦ μετὰ τῶν ἀποτελεσμάτων τῶν ἰσοτοπικῶν ἀναλύσεων δίδονται εἰς τοὺς χάρτας 1 καὶ 2.

Ἡ ἀκρίβεια τῶν ἀποτελεσμάτων τῶν ἀναλύσεων εἶναι τῆς τάξεως τοῦ $\pm 0.2\,^0/_{00}$ διὰ τὸ ^{18}O καὶ $\pm 2\,^0/_{00}$ διὰ τὸ Δευτέριον, ἐνῷ τὸ σφᾶλμα τῶν ἀναλύσεων Τριτίου καὶ ^{14}C δίδεται ὁμοῦ μετὰ τῶν ἀποτελεσμάτων τῶν σχετικῶν ἀναλύσεων.

4. 2. **Ταξινόμησις ἰσοτοπικῶν δεδομένων.**

4.2.1. **Ἰσοτοπικὰ δεδομένα ἀτμοσφαιρικῶν κατακρημνισμάτων.**

Περιοδικὴ δειγματοληψία ἐγένετο ἐκ δύο βροχομετρικῶν σταθμῶν (Χρυσομηλιᾶς - Μετεώρων) καὶ ἐκ τῶν βροχομέτρων τεσσάρων λυσιμέτρων (Κεφαλοβρύσου - Παλαιομοναστηρίου - Πουλιάνας καὶ Σαρακίνας). Ὡς ἐμφαίνεται εἰς τὴν εἰκόνα 1 ὑφίσταται μεγάλη ποικιλία τιμῶν $\delta^{18}O$, κυμαινομένη μεταξὺ $-2.4\,^0/_{00}$ καὶ $-12.7\,^0/_{00}$. Εἰς τὸ Σχ. 2 ἐμφαίνεται ἡ μεταβολὴ τοῦ $\delta^{18}O$ συναρτήσει τοῦ χρόνου, παρατηρεῖται δὲ ἐποχικὴ διακύμανσις τῆς περιεκτικότητος $\delta^{18}O$ τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων.

Εἰς τὴν εἰκόνα 3 ἔχουν προβληθῆ αἱ τιμαὶ $\delta^{18}O$ ἔναντι τῶν τιμῶν δD τῶν σταθμῶν Μετεώρων καὶ Χρυσομηλιᾶς τοῦ ἔτους 1969, διακρίνονται δὲ τὰ ἀτμοσφαιρικὰ κατακρημνίσματα τῶν διαφόρων ἐποχῶν.

Δεδομένου ὅτι αἱ ἐτήσιαι διαφοραὶ εἰς τὴν ἰσοτοπικὴν σύστασιν τοῦ ὕδατος τῶν βροχῶν καθωρισμένης περιοχῆς εἶναι μᾶλλον μικραὶ καὶ αἱ ἐποχικαὶ μεταβολαὶ εἶναι μᾶλλον ὁμοιόμορφοι, αἱ ὡς ἄνω τιμαὶ δύνανται νὰ χρησιμοποιηθοῦν διὰ τὸν καθορισμὸν τῆς συναρτήσεως εἰσόδου, ἀπὸ ἀπόψεως ἰσοτοπικῆς συνθέσεως, τῶν κατεισδύσεων εἰς τὴν ἐξεταζομένην περιοχήν.

Ἐκ τῆς εἰκόνος 4, εἰς τὴν ὁποίαν ἐμφαίνονται αἱ διαθέσιμοι τιμαὶ Τριτίου τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων καὶ ὑδρορρευμάτων, προκύπτει ὅτι τὰ ἀτμοσφαιρικὰ κατακρημνίσματα τῶν μὲν θερινῶν μηνῶν περιέχουν 300 T. U., τῶν δὲ χειμερινῶν μηνῶν περιέχουν 50 - 80 T. U.

4. 2. 2. Ἰσοτοπικὰ δεδομένα Λυσιμέτρων.

Περιοδικὴ δειγματοληψία ἐγένετο ἐκ τοῦ κατιόντος ὕδατος εἰς τέσσαρα λυσίμετρα. Ἐκ τῶν εἰκόνων 1 καὶ 2 γίνεται ἐμφανὲς ὅτι ἡ διακύμανσις τῆς ἰσοτοπικῆς συστάσεως εἶναι μικροτέρα εἰς τὸ κατιὸν ὕδωρ τῶν λυσιμέτρων, παρ' ὅ,τι εἰς τὸ ὕδωρ τῶν βροχομετρικῶν σταθμῶν. Τοῦτο ὀφείλεται εἰς ὁμαλοποίησιν, ἡ ὁποία λαμβάνει χώραν κατὰ τὴν κατείσδυσιν. Διὰ τοῦτο, γενικῶς, δείγματα κατιόντος ὕδατος λυσιμέτρων εἶναι λίαν χρήσιμα διὰ τὸν καθορισμὸν τῆς ἰσοτοπικῆς συστάσεως τοῦ τμήματος ἐκείνου τῶν κατακρημνισμάτων, τὰ ὁποῖα διεισδύουν κατ' εὐθεῖαν διὰ τῆς ἐπιφανείας. Αἱ μέσαι τιμαὶ $\delta^{18}O$ τοῦ κατιόντος ὕδατος τῶν λυσιμέτρων Σαρακίνης ($-7.4\,^0/_{00}$) καὶ Κεφαλοβρύσου ($-8.1\,^0/_{00}$) θὰ θεωρηθοῦν ἐντεῦθεν ὡς αἱ ἀντίστοιχοι μέσαι τιμαὶ τοῦ ὕδατος, τὸ ὁποῖον κατεισδύει ἀπ' εὐθείας ἐκ τῆς ἐπιφανείας εἰς τὸ Βόρειον καὶ Κεντρικὸν τμῆμα τῆς Θεσσαλικῆς πεδιάδος ἀντιστοίχως.

4. 2. 3. Ἰσοτοπικὰ δεδομένα ὑδρορρευμάτων.

Περιοδικὴ δειγματοληψία ἔλαβε χώραν ἐκ τοῦ Ποταμοῦ Πηνειοῦ καὶ τῶν παραποτάμων του Παμίσσου καὶ Πορταϊκοῦ. Ἐκ τῆς εἰκόνος 1 προκύπτει μικροτέρα διασπορὰ τῶν τιμῶν $\delta^{18}O$ τοῦ ὕδατος τῶν ὑδρορρευμάτων ἐν σχέσει πρὸς ἐκείνην τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων. Τοῦτο εἶναι φυσικὸν καὶ ὀφείλεται εἰς φαινόμενα ἀποθηκεύσεως, τὰ ὁποῖα παρατηροῦνται κατὰ τὴν διαδικασίαν βροχόπτωσις - ἀπορροή. Ἐκ τῶν εἰκόνων 1 καὶ 6 προκύπτει ὅτι τὸ ὕδωρ τῶν Παμίσσου καὶ Πορταϊκοῦ παρουσιάζει παρομοίαν τιμὴν $\delta^{18}O$ ὡς καὶ παρομοίαν μεταβολὴν αὐτῆς μετὰ τοῦ χρόνου, ἐνῷ τὸ ὕδωρ τοῦ Πηνειοῦ παρουσιάζει χαμηλοτέραν τιμὴν $\delta^{18}O$ λόγῳ, προφανῶς, διαφόρου γεωγραφικοῦ καὶ τοπογραφικοῦ προσανατολισμοῦ τῶν ἀντιστοίχων λεκανῶν ἀπορροῆς. Αἱ ἀντίστοιχοι μέσαι τιμαὶ $\delta^{18}O$ ($-8.7\,^0/_{00}$ διὰ τοὺς ποταμοὺς Πάμισσον καὶ Πορταϊκὸν καὶ $-9.2\,^0/_{00}$ διὰ τὸν Πηνειὸν) θὰ χρησιμοποιηθοῦν κατὰ τὴν διερεύνησιν ἐνδεχομένης συμβολῆς τῶν ποταμῶν τούτων εἰς τὴν τροφοδοσίαν τῶν ὁριζόντων τῆς Θεσσαλικῆς πεδιάδος.

Ἐκ τῆς εἰκόνος 4 προκύπτει ὅτι ἡ εἰς Τρίτιον περιεκτικότης τῶν ποταμῶν Πορταϊκοῦ, Παμίσσου καὶ Πηνειοῦ εἶναι μᾶλλον ὁμοιόμορφος, ἀνερχομένη εἰς 150 - 200 T. U.

4. 2. 4. Ἰσοτοπικὰ δεδομένα πηγῶν καὶ φρεάτων.

Τὰ ἰσοτοπικὰ δεδομένα ἐκ φρεάτων καὶ πηγῶν ἀντιστοιχοῦν εἰς εὐρέως διεσπαρμένα σημεῖα δειγματοληψίας, ἡ δὲ ἰσοτοπικὴ σύνθεσις τῶν ἐν λόγῳ ὑδάτων ἐπέτρεψε τὴν μελέτην τόσον τοῦ μηχανισμοῦ, ὅσον καὶ τῆς προελεύσεως τῆς τροφοδοσίας τῶν ὑδροφόρων ὁριζόντων τῆς λεκάνης Δυτικῆς Θεσσαλίας. Ἡ ὑδροδυναμικὴ τοῦ συστήματος ἐμελετήθη μέσῳ ἀναλύσεων διὰ Τρίτιον καὶ ^{14}C, ὡς θὰ ἴδωμεν περαιτέρω.

Εἰς τὸν Χάρτην 1 ἐμφαίνονται αἱ θέσεις τῶν πηγῶν, ἐκ τῶν ὁποίων ἐγένετο περιοδικὴ δειγματοληψία ὁμοῦ μετὰ τῶν τιμῶν δ^{18}O καὶ Τριτίου. Ἐκ τῆς εἰκόνος 1 προκύπτει ὅτι αἱ τιμαὶ δ^{18}O δι' ὅλας τὰς πηγὰς κυμαίνονται μεταξὺ — 8 καὶ — 9 ‰ μὲ μερικὰς μόνον ἐξαιρέσεις, αἵτινες παρουσιάζουν ὑψηλοτέρας ἢ χαμηλοτέρας τιμὰς (ὑψόμετρον ἢ εἶδος τροφοδοσίας ἢ ἀμφότερα). Αἱ μικραὶ μόνον διακυμάνσεις τῆς τιμῆς δ^{18}O συναρτήσει τοῦ χρόνου (εἰκόνες 1 καὶ 3), ὀφείλονται εἰς τὴν ἐκ τῆς ἀποθηκεύσεως ὁμαλοποίησιν.

Εἰς τὸν Χάρτην 2 ἐμφαίνονται αἱ θέσεις τῶν φρεάτων, ἐκ τῶν ὁποίων ἐλήφθησαν δείγματα ὕδατος, ὡς καὶ αἱ ἀντίστοιχοι τιμαὶ δ^{18}O, Τριτίου καὶ ^{14}C.

4. 3. Ἑρμηνεία - Ἀξιολόγησις τῶν ἀποτελεσμάτων.

4. 3. 1. Γενικαὶ Παρατηρήσεις ἐπὶ τῆς ἀντιπροσωπευτικότητος τῶν δειγμάτων.

Αἱ μεγαλύτεραι δυσχέρειαι εἰς τὴν ἑρμηνείαν τῶν ἀποτελεσμάτων προέρχονται ἐκ τοῦ γεγονότος ὅτι αἱ διάφοροι γεωτρήσεις, ἀλλὰ καὶ πηγαὶ ὑδρομαστεύουσαι ἀλλεπάλληλα ὑδροφόρα στρώματα, συχνὰ δίδουν ὕδωρ μὲ διάφορον βαθμὸν ἀναμίξεως ἐκ τῶν ἐν λόγῳ ὑδροφόρων στρωμάτων.

4. 3. 2. Ἑρμηνεία καὶ ἀξιολόγησις ἀποτελεσμάτων ἀναλύσεων ^{18}O καὶ D εἰς δείγματα πηγῶν καὶ γεωτρήσεων.

4. 3. 2. 1. Πηγαί.

Ἐκ τοῦ σχήματος 8 καθορίζεται ἡ σχέσις μεταξὺ τιμῆς δ^{18}O καὶ μέσου ὑψομέτρου τῆς περιοχῆς τροφοδοσίας. Πρὸς τὸν σκοπὸν τοῦτον ἐχρησιμοποιήθησαν πηγαὶ τῆς Δυτικῆς ὀρεινῆς περιοχῆς ἢ τοιαῦται παρὰ τοὺς πρόποδας λόφων (Κάππα, Πόρτα-Παναγιᾶς, Κοτρώνι, Τύρνας, Ξυλοπάρικου καὶ Ἀμαράντου) τῶν ὁποίων εἶναι μᾶλλον γνωστὴ ἡ περιοχὴ τροφοδοσίας των. Ἡ κλίσις τῆς εὐθείας τοῦ σχήματος 8 ἀντιστοιχεῖ εἰς — 0.2 ‰ δ^{18}O ἀνὰ 100 m ὑψομετρικῆς διαφορᾶς, τιμὴ ἡ ὁποία εἶναι γενικῶς ἀποδεκτή. Ἡ σχέσις αὕτη, ὡς φαίνεται ἐκ τοῦ σχήματος 8, ἰσχύει καὶ διὰ τὰς πηγὰς τῆς Βορείου ὀρεινῆς περιοχῆς (Βασιλικῆς, Θεοπέτρας, Χειμαδιοῦ) ὡς καὶ διὰ τὰς πηγὰς Ζωγραφιᾶς, Ρούσου καὶ λόφου Ρούσου τῆς νοτίας πλευρᾶς.

Ἐκ τῆς τιμῆς δ^{18}O τῶν πηγῶν Γοργογυρίου καὶ Μοράβας προσδιορίζεται, τῇ βοηθείᾳ τοῦ σχήματος 8, ὅτι τὸ μέσον ὑψόμετρον τῆς περιοχῆς τροφοδοσίας των ἀνέρχεται εἰς 800 καὶ 1.200 - 1.300 m ἀντιστοίχως.

Ἐπὶ τῇ βάσει τῶν τιμῶν δ^{18}O καὶ Τριτίου τοῦ ὕδατος ἐκ διαφόρων προελεύσεων (ποταμῶν, τοπικῶν κατεισδύσεων καὶ κατεισδύσεων εἰς τὴν Βόρειον ὀρεινὴν περιοχὴν) καὶ τῶν ἀντιστοίχων τοιούτων πηγῶν, αἱ ὁποῖαι εὑρίσκονται εἰς τὴν προσχωσιγενῆ πεδιάδα, προσδορίζεται διὰ μαθηματικῆς ἐπεξεργασίας τὸ ποσοστὸν συμμετοχῆς ἑκάστης ἐκ τῶν τριῶν τούτων προελεύσεων εἰς τὴν τροφοδοσίαν τῶν ἀλλουβιακῶν πηγῶν τῆς πεδιάδος. Οὕτω προσδιωρίσθη ὅτι αἱ πηγαὶ τοῦ κεντρικοῦ τμήματος ὁλοκλήρου τῆς Θεσσαλικῆς πεδιάδος τροφοδοτοῦνται κατὰ κύριον λόγον ἀπὸ τὸ ὕδωρ τῶν παρακειμένων ποταμῶν, δευτερευόντως δὲ ἀπὸ τοπικὰς κατεισδύσεις.

4. 3. 2. 2. Γεωτρήσεις.

Ἐκ τῆς εἰκόνος 1 προκύπτει ὅτι ἡ ἰσοτοπικὴ σύνθεσις τοῦ ὕδατος τῶν γεωτρήσεων τοῦ Δυτικοῦ καὶ Βορείου τμήματος τῆς κοιλάδος γενικῶς διαφέρει σημαντικῶς ἀπὸ ἐκείνην τοῦ ὕδατος τῶν γεωτρήσεων αἱ ὁποῖαι κεῖνται εἰς τὸ ΝΑ/κὸν τμῆμα τῆς κοιλάδος, λόγῳ διαφόρου μηχανισμοῦ τροφοδοσίας.

Ἐκ τῆς εἰκόνος 9 προκύπτει ὅτι γενικῶς ὑφίσταται ἀλληλοεπικάλυψις τῶν διαφόρων ἰσοτοπικῶν συνθέσεων τῶν ληφθέντων δειγμάτων (ἐκ λυσιμέτρων, ὑδρορρευμάτων καὶ πηγῶν) μὲ ἀποτέλεσμα νὰ δυσχεραίνεται ὁ καθορισμὸς μὲ κατηγορηματικὸν τρόπον τῆς προελεύσεως τοῦ ὑπογείου ὕδατος (πηγὴ τροφοδοσίας ὑδροφόρων ὁριζόντων).

Διὰ τὸν ὑδροφόρον ὁρίζοντα τοῦ Βορείου τμήματος τῆς λεκάνης δύναται νὰ λεχθῇ ὅτι ἡ κυρία τροφοδοσία προέρχεται ἐκ τοῦ Πηνειοῦ (τιμαὶ δ^{18}O τῶν γεωτρήσεων κυμαινόμεναι ἀπὸ — 8.6 ‰ ἕως — 9 ‰, δ^{18}O Πηνειοῦ — 9.2 ‰). Κατὰ τὸν ἴδιον τρόπον εἶναι πιθανὸν γεωτρήσεις μεταξὺ τῶν ποταμῶν Παμίσσου καὶ Πορταϊκοῦ καὶ ἔτι δυτικώτερον νὰ τροφοδοτοῦνται κατὰ κύριον λόγον ἀπὸ τοὺς ποταμοὺς αὐτούς.

Αἱ χαμηλαὶ τιμαὶ δ^{18}O, αἵτινες παρετηρήθησαν εἰς τὰς γεωτρήσεις τοῦ ΝΑ/κοῦ τμήματος (— 9.0 ‰ ἕως — 10.3 ‰), ὡς ἐμφαίνεται εἰς τὴν εἰκόνα 1 καὶ τὸν χάρτην 2, ὑποδηλοῦν ὅτι ἡ τροφοδοσία τῶν ὑδροφόρων τῆς περιοχῆς γίνεται ἀπὸ ὑψόμετρα μεγαλύτερα τῶν 1.000 μ. Δοθέντος ὅμως ὅτι πρόκειται περὶ ὕδατος ἡλικίας μεγαλυτέρας τῶν 30.000 ἐτῶν, αἱ χαμηλαὶ αὗται τιμαὶ δ^{18}O θὰ ἠδύναντο νὰ ἀποδοθοῦν καὶ εἰς παλαιοκλιματικὰς μεταβολὰς τῆς περιοχῆς.

4. 3. 3. Ἑρμηνεία καὶ ἀξιολόγησις ἀποτελεσμάτων Τριτίου καὶ ^{14}C εἰς δείγματα γεωτρήσεων καὶ πηγῶν.

4. 3. 3. 1. Ποιοτικὴ ἑρμηνεία.

Εἰς τὴν εἰκόνα 4 ἐμφαίνονται αἱ συγκεντρώσεις Τριτίου τῶν ἀτμοσφαιρικῶν καρακρημνισμάτων ἐκ τῶν βροχομέτρων, τῶν λυσιμέτρων καὶ τῶν ὑδρορρευμάτων. Ἡ ὑψηλὴ συγκέντρωσις Τριιίου εἰς τὰς πηγὰς καὶ τὰς γεωτρήσεις τοῦ Δυτικοῦ καὶ Βορείου τμήματος τῆς κοιλάδος, ἤτοι εἰς τὰς γεωτρήσεις D - 3, D - 1, D - 2, D - 4 καὶ D - 5 καὶ εἰς ἁπάσας τὰς πηγὰς τῆς περιοχῆς φανερώνει μικρὸν χρόνον παραμονῆς τοῦ ὕδατος εἰς τὰ ὑδροφόρα στρώματα.

Αἱ χαμηλαὶ συγκεντρώσεις Τριτίου εἰς τὰς γεωτρήσεις τοῦ κεντρικοῦ τμήματος τῆς κοιλάδος, ἤτοι εἰς τὰς γεωτρήσεις D - 16, D - 12, D - 13, D - 15, φανερώνουν μικρὰν ταχύτητα ροῆς ὑπογείου ὕδατος. Περαιτέρω πρὸς Ἀνατολὰς καὶ εἰς τὸ ΝΑ/κὸν τμῆμα τῆς περιοχῆς ὅλαι αἱ γεωτρήσεις εἶναι ἐλεύθεραι Τριτίου, ἐνῷ τὰ δεδομένα ^{14}C ὑποδηλοῦν ἡλικίαν ὕδατος τουλάχιστον 30.000 ἐτῶν (λίαν μικρὰ ταχύτης ροῆς καὶ πτωχὴ τροφοδοσία τῶν ὑδροφόρων ὁριζόντων). Ἐκ τοῦ γεγονότος ὅτι ἡ ἡλικία τοῦ ὕδατος τῆς γεωτρήσεως D - 10 εἶναι πρόσφατος, τῶν δὲ γεωτρήσεων D - 13 καὶ D - 15 2.500 καὶ 3.450 ἔτη ἀντιστοίχως, προκύπτει ὅτι εἰς τὸ ἐν λόγῳ τμῆμα τῆς κοιλάδος ἡ ταχύτης ροῆς τοῦ ὑπογείου ὕδατος ἀνέρχεται εἰς 5 m / ἔτος.

4.3.3.2. Ποσοτικὴ ἐπεξεργασία.

Εἰς τὴν Βιβλιογραφίαν [**6**, **7**] ἀναφέρονται διάφορα μαθηματικὰ πρότυπα διὰ τὴν ποσοτικὴν ἐπεξεργασίαν τῶν δεδομένων τῆς ἀναλύσεως Τριτίου τῶν φυσικῶν ὑδάτων. Διὰ τὴν συγκεκριμένην περίπτωσιν ἐπελέξαμεν τὸ πρότυπον τῶν διαδοχικῶν ρεζερβουάρ, ἕκαστον τῶν ὁποίων δρᾷ ὡς καλὸς ἀναμίκτης, μὲ τὸν αὐτὸν μέσον χρόνον παραμονῆς τοῦ ὕδατος εἰς αὐτὰ $\left(\frac{V}{Q} = K\right)$.

Εἰς τὴν περίπτωσιν ταύτην ἡ συνάρτησις ἀποκρίσεως συστήματος ἐκ «n» «ρεζερβουὰρ» δίδεται [**7**] ἀπὸ τὸν τύπον (1)

$$f_T(T) = \frac{1}{K} \, \frac{(t/K)^{n-1} \cdot e^{-t/K}}{(n-1)\,!} \tag{1}$$

Διὰ δεδομένην συνάρτησιν εἰσόδου εἰς τὸ σύστημα τοῦτο, ἡ συνάρτησις ἐξόδου τούτου, ὑπολογίζεται διὰ τοῦ κάτωθι ὁλοκληρώματος τῆς ἀνελείξεως (convolution Integral).

$$C(t) = \int_0^{\infty} f_i(t - T) \cdot f_T(T) \cdot dT$$

Εἰς τὸ μαθηματικὸν τοῦτο πρότυπον ὑπεισέρχονται δύο παράμετροι, ἤτοι ὁ μέσος χρόνος παραμονῆς τοῦ ὕδατος εἰς ἕκαστον ρεζερβουὰρ καὶ ὁ συνολικὸς ἀριθμὸς τῶν ρεζερβουάρ.

Εἰς τὴν συγκεκριμένην περίπτωσιν, λόγῳ τοῦ μικροῦ ἀριθμοῦ ἀναλύσεων Τριτίου δι' ἑκάστην πηγὴν ἢ γεώτρησιν ἠναγκάσθημεν ὅπως θεωρήσωμεν δεδομένον τὸν ἀριθμὸν τῶν ρεζερβουάρ. Οἱ σχετικοὶ ὑπολογισμοὶ ἔλαβον χώραν εἰς ὑπολογιστῆρα WANG 700, ἀναφέρονται δὲ εἰς σύστημα ἀποτελούμενον ἀπὸ δύο διαδοχικὰ ρεζερβουάρ.

Διὰ τὸν προσδιορισμὸν τῆς εἰσόδου Τριτίου (εἰκ. 11) ἐχρησιμοποιήθησαν ἀποτελέσματα ἀναλύσεων ὑδάτων σταθμῶν τῆς περιοχῆς διὰ τὰ ἔτη 1968 ἕως 1971. Διὰ τὴν προγενεστέραν περίοδον ἐλήφθησαν τιμαὶ ἐκ συσχετισμοῦ [**8**] πρὸς ἀποτελέσματα ἀναλύσεων ἐκ τῶν σταθμῶν Ἀθηνῶν καὶ Ὀττάβας (εἰκ. 10). Εἰς τὴν εἰκόνα 11 δίδονται ἐπίσης αἱ ὑπολογισθεῖσαι τιμαὶ ἐξόδου Τριτίου διὰ διαφόρους μέσους χρόνους μεταφορᾶς. Εἰς τὴν εἰκόνα 12 δίδονται αἱ ὑπολογισθεῖσαι καμπύλαι ἐξόδου Τριτίου, ὁμοῦ μετὰ τῶν τιμῶν Τριτίου τῶν διαφόρων πηγῶν καὶ γεωτρήσεων.

Ἡ ἐκτιμηθεῖσα μικροτέρα πιθανὴ ἡλικία τῶν διαφόρων πηγῶν καὶ ὁ ἐξ αὐτῆς ὑπολογισθεὶς ἐλάχιστος ὄγκος τῆς ἀντιστοίχου λεκάνης ἀποθηκεύσεως δίδονται εἰς τὸν πίνακα 3.

Ἀναφορικῶς πρὸς τὰ ὑπόγεια ὕδατα, αἱ παρατηρηθεῖσαι τιμαὶ Τριτίου εἰς τὸ Βόρειον τμῆμα τῆς κοιλάδος (Λεκάνη Καλαμπάκας) δίδουν μέσην ἡλικίαν εἰς τὰς γεωτρήσεις D - 1, D - 2, D - 4, D - 5, 4 - 15 ἐτῶν. Ἡ ἡλικία ἐπίσης τοῦ ὕδατος τῶν γεωτρήσεων D - 18 καὶ D - 20 ἐκτιμᾶται εἰς 4 - 10 ἔτη. Ἀντιθέτως εἰς τὸ κέντρον τῆς κοιλάδος αἱ πολὺ χαμηλαὶ τιμαὶ Τριτίου ὑποδηλοῦν μίαν ἐλαχίστην ἡλικίαν 75 ἐτῶν. Τὰ προαναφερθέντα βεβαίως εἰς τὴν παροῦσαν παράγραφον συνιστοῦν μίαν χονδρικὴν ἐκτίμησιν, ἥτις δύναται νὰ γίνῃ βεβαιότης μόνον διὰ τῆς συγκρίσεως πρὸς τὰ ἀποτελέσματα τῶν δεδομένων τῆς βασικῆς ὑδρολογικῆς καὶ ὑδρογεωλογικῆς ἐρεύνης.

5. ΣΥΜΠΕΡΑΣΜΑΤΑ

1. Ἡ τροφοδοσία τῶν ὑδροφόρων ὁριζόντων τοῦ βορειοτάτου τμήματος τῆς κοιλάδος (ὑπολεκάνη Καλαμπάκας) προέρχεται κατὰ 60 % ἐκ τοῦ Πηνειοῦ καὶ τῶν παραποτάμων αὐτοῦ καὶ 40 % ἐκ τοπικῆς κατεισδύσεως τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων.

2. Ἡ σταθερὰ ἰσοτοπικὴ σύνθεσις τοῦ ὑπογείου ὕδατος τοῦ ΝΑ/κοῦ τμήματος τῆς κοιλάδος Δ. Θεσσαλίας εἶναι σημαντικῶς διάφορος ἀπὸ ἐκείνην τοῦ Δυτικοῦ καὶ Βορείου τμήματος, ἔνθα καὶ ὁ μηχανισμὸς τροφοδοσίας εἶναι διάφορος.

3. Ἡ ἰσοτοπικὴ σύνθεσις τῶν πηγῶν τῆς ὀρεινῆς καὶ λοφώδους περιοχῆς ἐπέτρεψαν τὸν προσδιορισμὸν τοῦ μέσου ὑψομέτρου τῆς περιοχῆς τροφοδοσίας των, τὸ ὁποῖον γενικῶς εἶναι μεγαλύτερον τῶν 500 - 600 μ. Αἱ πηγαὶ Μικροῦ καὶ Μεγάλου Κεφαλοβρύσου τροφοδοτοῦνται κυρίως ἐκ τοῦ Πηνειοῦ κατὰ δεύτερον δὲ λόγον ἐκ τῆς τοπικῆς κατεισδύσεως τῶν ἀτμοσφαιρικῶν κατακρημνισμάτων εἰς τὸ ἀλλουβιακὸν πεδίον.

4. Τὰ δεδομένα Τριτίου καὶ ^{14}C ὑποδηλοῦν ὅτι εἰς τὸ Βόρειον καὶ Δυτικὸν τμῆμα τῆς κοιλάδος ἡ ταχύτης ροῆς τοῦ ὑπογείου ὕδατος εἶναι μεγάλη καὶ

ἡ ἡλικία τούτου 4 - 15 ἔτη, ἐνῷ εἰς τὸ κεντρικὸν τμῆμα τῆς κοιλάδος ἡ ταχύτης ροῆς εἶναι τῆς τάξεως τῶν 5 μ / ἔτος, ἡ δὲ μέση ἡλικία τοῦ ὑπογείου ὕδατος 75 ἔτη.

5. Ἡ πολὺ μεγάλη ἡλικία τοῦ ὑπογείου ὕδατος τῆς νοτίου περιοχῆς ὑποδηλοῖ ὅτι ἡ κίνησις τοῦ ὕδατος εἶναι πολὺ μικρὰ καὶ ἡ τροφοδοσία τῶν ὑδροφόρων ὁριζόντων κακή.

6. Αἱ τιμαὶ Τριτίου κατέστησαν δυνατὸν τὸν καθορισμὸν τῆς ἡλικίας τοῦ ὕδατος τῶν πηγῶν καὶ τοῦ ὄγκου τῆς λεκάνης ἀποθηκεύσεως τούτων.

REFERENCES

1. KALLERGIS, G. A. 1970.— Hydrogeological Investigation of the Kalambaka Basin (Western Thessaly); *Institute for Geology and Subsurface Research,* vol. **XIV**, No 1, Athens; (in Greek with English Summary), 197 p.
2. PAYNE, BR. 1971. — Environmental Isotope Techniques for the Hydrologist. *J. Brit. Nucl. Energy Soc.;* Jan. 1971, p. 29 - 32.
3. INTERNATIONAL ATOMIC ENERGY AGENGY, 1968.— Guidebook on Nuclear Techniques in Hydrology. *Techn. Reports Series* No. 91, 213 p.
4. CRAIG, H. 1961.— Isotopic variations in meteoric waters. *Science,* **133**, p. 1833-34.
5. DANSGAARD, W. 1964. — Stable isotopes in precipitation. *Tellus,* **16**, 436.
6. NIR, A 1967.— Development of isotope methods applies to groundwater hydrology; Proc. Symp. on Isotope Techniques in the Hydrologic Cycle. *A. G. U. Monograph Series,* No. 11, 109.
7. BEAR, J. et al., 1968. — Physical Principles of Water Percolation and Seepage; *UNESCO, Arid Zone Research,* **XXIX,** Chapter 11, Hydrodynamic Dispersion.
8. DIMITROULAS, C. - LEONTIADIS, J. 1973.— Environmental tsotopes as tracers for studies of the water movement in nature. *DEMO,* 73/2 C.

TABLE 4.

Isotope data from springs and wells Western Thessaly.

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
D - 12	11/ 9/68	drilled well	WL = — 1.25 m Alluvium ; unconfined, Perf. 10 - 42 m ; T = 15° C	103	1.3 ± 0.5	— 57	— 8.3	— 14.6	19.9 ± 0.7	Maybe another sample
	21/ 5/69	12 m			0.9 ± 0.3	— 51	— 8.7			
	8/ 7/69							— 13.0	58.6 ± 1.5	
D - 13	11/ 9/68	drilled well 125 m	WL = + 4 m Alluvium ; confined zones 2, 3, or more, Perf. 75-123.9 m. Flows 60 m³ / hr. T = 15° C Cond : 235 μmhos	103	1.7 ± 0.2	— 47	— 7.9	— 13.9	41.1 ± 1.1	«age» discussed under Carbon isotope data
D - 15	11/ 9/68	drilled well 149 m	WL = + 12 m Alluvium ; confined zones, 2, 3, or more, Perf. 137-149 m, T = 15.2° C ; flows 80 m³ / hr. Cond : 240 μmhos	103	1.6 ± 0.2	— 52	— 8.7	— 15.6	41.1 ± 1.2	»
D - 16	13/12/68	drilled well	WL = + 11.70 for 33 - 44 m interval ; Pebbles, sand conf. aquifer Flows 18 m³ / hr, T = 14° C	120	4.0 ± 1.0	— 54	— 8.8			
	18/ 4/69	158.3 m			7.5 ± 0.4	— 52	— 8.9			
	22/ 4/69		WL = + 8.42 m for 50 - 64 m interval ; Flows 51 m³ / hr, T = 13.8° C			— 54	— 9.0			
	24/ 4/69		WL = + 12.19 m for 74 - 88 m interval ; Flows 46.5 m³ / hr, T = 13.0° C			— 55	— 8.7			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
D - 17	8/ 7/69	drilled well 90 m	same as D - 16	120				— 11.3	66.0 ± 1.6	«Age» discussed under Carbon isotope data
D - 4	12/ 9/68	drilled well 216.5 m	WL = — 4 m Alluv., confined or semiconfined (referred to as transition zone) Perf. 6 - 135.2 Yld. 109 m^3 / hr. Cond. = 310 μmhos	127	109 ± 4	— 56	— 8.7			
D - 5	12/ 9/68	drilled well 30 m	WL = — 5.5 m unconfined alluv., 0 - 30 m WL fluctuates ± 1 m seasonally	127	304 ± 11	— 56	— 8.6			
	8/ 1/69		»	»	268 ± 13	— 55	— 8.6			
D - 10	12/ 9/68	drilled well 148.5 m	WL = — 2 m semi-confined alluvium. Pumped Yld: 148 m^3 / hr. Perf. 18 - 110 sev. WB layers, seasonal variat. in WL to 3 m above LSD (spr. summer)	125	37.7 ± 1.5	— 56	— 8.8	— 12.2	87.8 ± 2.0	»
D - 3	21/11/68	drilled well 132.8 m	WL = — 3 m semi-confined alluvium. Perf. 11-120 m. Yld. 120 m^3/hr.	206	30.4 ± 1.9	— 59	— 9.0			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D $^0/_{00}$ from SMOW	^{18}O $^0/_{00}$ from SMOW	^{13}C $^0/_{00}$ from PDB	^{14}C $^0/_0$ modern	Remarks
D - 9	22/11/63	drilled well 17 m	WL = — 3 m; unconfined alluvium. Perf. 0 - 17. WB: 3 - 7.5 m	130	69.7 ± 4	— 57	— 8.7			
D - 2	22/11/68	drilled well 155 m	WL = — 11 m unconfined alluvium. Perf. 0 - 106. WB: 12 - 67; 80 - 90; 92 - 105. Yld. 145 m³ / hr.	145	307 ± 11	— 56	— 8.9			
D - 1	22/11/68	drilled well 141 m	WL = — 25 m unconfined alluvium. Perf. 0 - 113.5 various WB zones Yld. 120 m³ / hr.	155.5	201 ± 7	— 55	— 8.7			
G - 501	10/10/69	drilled well 95 m	WL = — 1.5 m confined alluvium Several WB layers	100	0 ± 5		— 8.9			Not in bedrock at 300 m
D - 18	10/10/69	drilled well 172.5 m	WL = — 20 m unconfined (or semi) in alluvium se. Perf. 77 - 105; 110 - 162. Yld. 104 m³ / hr.	146	256 ± 9		— 8.4			
D - 20	10/10/69	drilled well 107 m	WL = — 44 m unconfined in alluvium. Perf. 19 - 89 m	173	199 ± 7		— 8.5			
D - 21	10/10/69	drilled well 177 m	WL = — 1 m confined aquifer in alluvium. Perf. 22 - 117 m	122	0 ± 5		— 8.6			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T.U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
G - 402	10/10/69	drilled well 166 m	WL = —5 m confined alluvium. Perf. 10 - 12 ; 30 - 38 ; 114 - 116 ; 120 - 123 ; 160 - 164. Yld. 46 m^3 / hr.	140	0 ± 5		—8.6			
G - 401	10/10/69	drilled well 105 m	WL = —1 m ; confined alluvium. Perf. 9 - 13 ; 19 - 23 ; 25 - 29 ; 47 - 103. Yld. 60 m^3 / hr.	140	93.9 ± 8.1		— 7.5			
D - 22	14/11/69	drilled well 175 m	WL = —7.7 m confined alluvium. Perf. 12 - 127 ; 129 - 134 ; 134 - 154. Yld. 80 m^3 / hr.	105	77.9 ± 10.6		— 7.7			
D - 23	14/11/69	drilled well 192 m	WL = —2.17 confined alluvium. Perf. 12 - 72 ; 84 - 150 (open)	94	— 6.3 ± 5.0		— 8.8			
G - 403	15/11/69	drilled well 130 m	WL = —1 m confined alluvium. Perf. 13 - 15 ; 16 - 25 ; 42 - 67 ; 114 - 116 ; 127 - 130. Yld. 53 m^3 / hr.	99	1.4 ± 0.4		— 8.1			
G - 404	15/11/69	drilled well 157 m	WL = —1.98 confined alluvium. Perf. 12 - 15; 17 - 18; 27 - 30; 62 - 79; 85 - 87 ; 94 - 96 ; 141 - 143 ; 150 - 157.	100	— 5.4 ± 4.8		— 9.0			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
G - 405	15/11/69	drilled well 150 m	WL = − 4.0 confined alluvium. Perf. 20 - 84 ; 145 - 150. Yld. 55 m^3/hr.	99	2.0 ± 0.4		− 8.7			
G - 406	15/11/69	drilled well 177 m	WL = − 1.4 m confined alluvium. Perf. 44 - 50; 64 - 68; 74 - 76; 102 - 116; 140 - 166 ; 170 - 176. Yld. 25 m^3 / hr.	114	− 2.0 ± 5.8		− 9.3			
G - 407	15/11/69	drilled well 154 m	WL = + 0.30 confined alluvium. Perf. 28 - 42 ; 72 - 74 ; 102 - 110 ; 114 - 120 ; 142 - 152.	97			− 10.1			
	25/ 5/71							− 16.04	0.7 ± 0.5	
	7/ 1/69				46.9 ± 2.3	− 52	− 8.4			
G - 408	23/11/69	drilled well 120 m	WL = − 2.03 confined alluvium. Perf. 3 - 8 ; 10 - 12 ; 16 - 17 ; 20 - 32 ; 34 - 36 ; 44 - 48 ; 56 - 64 ; 68 - 78 ; 80 - 82 ; 90 - 100 ; 114 - 118.	96	1.8 ± 0.4		− 10.1			Marble at 125 m
	25/ 5/71							− 10.42	0.2 ± 0.6	
G - 409	12/ 1/70	drilled well 80 m	WL = − 8.70 confined alluvium. Perf. 3 - 7 ; 32 - 78.	83.5	− 2.9 ± 4.6 1.1 ± 3.6		− 9.8			Black conglomerate at 215 m

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
	25/ 5/71							— 5.84	1.1 ± 0.4	
G - 502	15/11/69	drilled well 145 m	WL=+1.50 confined alluvium. Perf. 16-18; 40-42; 58-60; 84-88; 92-104; 128-145. T = 17.5° C. Yld. 30m^3/hr.	130	1.6 ± 0.3		— 8.9			
G - 503	23/11/69	drilled well 120 m	WL = — 2.85 confined alluvium. Perf. 10-14; 26-30; 50-58; 96-102; 106-112; 114-120.	103	—5.9 ± —5.4 or 0 ± 5		—10.3			Bedrock at 230 m
G - 504	23/11/69	drilled well 102 m	WL = — 2.56 confined alluvium. Perf. 10-20; 36-38; 60-78; 90-100. (near stream)	100	15.3 ± 9.1		— 8.6			Bedrock at 265 m
G - 505	23/11/69	drilled well 232 m	WL = — 2.70 confined alluvium. Perf. 8-12; 28-34; 46-52; 64-66; 74-80; 98-110; 124-130; 132-138; 174-198; 212-230.	95	9.8 ± 6.4		— 9.5			Bedrock at 24.6 m
	10/ 3/71				2.0 ± 0.4		— 9.9	+ 0.94	0.9 ± 0.5	Conglomerate at 250 m
G - 506	23/11/69	drilled well 42 m	WL = — 3.74 confined alluvium. Perf. 8-40.	96	19.4 ± 4.9		— 9.3			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D $^{0}/_{00}$ from SMOW	^{18}O $^{0}/_{00}$ from SMOW	^{13}C $^{0}/_{00}$ from PDB	^{14}C $^{0}/_{0}$ modern	Remarks
Morava	14/11/68	Spring	0.3 m^3 / sec. T = 5.5° C	704	272 ± 9	— 65	— 10.5			West of area on Fig. 1 (recharge zone)
Chtouri	12/11/68	»	0.02 m^3 / sec. T = 17.5° C	116	0	— 52	— 8.1			
Amaradon	14/11/68	»	50 m^3 / hr. T = 9.0° C	1180		— 59	— 10.0			West of area on Fig. 1
Mega-Kephal.	12/11/68	»	0.27 m^3 / sec. T = 13° C	127	161 ± 6	— 44	— 6.8			Unconfined alluvium
Micro-Kephal.	12/11/68	»	0.4 m^3 / sec. T = 14° C	124	252 ± 9	— 55	— 8.8			» »
Kotroni	12/11/68	»	T = 12° C	730	253 ± 10	— 51	— 8.7			«karstic water»
Keramidhi	12/11/68	»	0.02 m^3 / sec. T = 18° C	100		— 49	— 8.4			» »
Klokotos	12/11/68	»	0.02 m^3 / sec. T = 17° C	95	53.3 ± 2.8	— 53	— 8.2			» »
Amourion	20/11/68	»	0.02 m^3 / sec. T = 15° C		120 ± 5	— 50	— 8.2			» »
Kourtikion	12/11/68	»	0.01 m^3 / sec. T = 19° C	100	16.9 ± 0.8	— 54	— 8.5			» »
Voula	12/11/68	»	0.41 m^3 / sec. T = 16.5° C	93	43.4 ± 6.8	— 53	— 8.7			«karstic water»
Voula	10/ 3/71	»			28.6 ± 5.2		— 8.1			
Gomphi (A)	10/11/68	»	T = 14° C	130	165 ± 7	— 52	— 8.4			Alluvium
Moni Vitouma	8/11/68	»	T = 11° C		211 ± 9	— 53	— 8.5			Contact between ls. and igneous rock

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
Kappa	10/11/68	Spring	0.2 m^3 / hr. T = 14° C	128	181 ± 9	— 51	— 7.9			«karstic water»
Diava	10/11/68	»	0.8 m^3 / hr. T = 14° C			— 49	— 7.5			» »
Loxadha	10/11/68	»	— T = 16° C	100	57.3 ± 2.6	— 51	— 8.2			Conglom. & sand. Oligocene
Charmaina	10/11/68	»	0.2 m^3 / hr. T = 15° C	130		— 52	— 8.4			»
Zografia	10/11/68	»	0.5 m^3 / hr. T = 13.5° C	123		— 49	— 7.9			Alluvial Aquifer
Vassiliki	10/11/68	»	0.02 m^3 / hr. T = 14° C	147		— 48	— 7.3			karstic aguifer
Kephalovrisso	19/11/68	»	0.2 m^3 / sec.		32.9 ± 8.7	— 53	— 8.8			NE of area on Fig. 1
Dipotamos	10/11/68	»	0.3 m^3 / hr. T = 15° C	120	41.9 ± 2.2	— 55	— 9.0			large fluct.
Tirna	7/11/68	»	7.0 m^3 / hr. T = 10° C	850		— 52	— 8.9			Contact spring Flysh/ls.
Gorgoyirion	11/11/68	»	15.0 m^3 / hr. T = 9.5° C	250	193 ± 22	— 55	— 9.0			«karstic water»
Porta Panayia	7/11/68	»	3.0 m^3 / hr.			— 51	— 8.3			»

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T. U.	D °/₀₀ from SMOW	^{18}O °/₀₀ from SMOW	^{13}C °/₀₀ from PDB	^{14}C °/₀ modern	Remarks
Mega Pouliana	10/11/68	Spring	T = 13° C	121	210 ± 9	— 51	— 8.4			
Rousson (River Bank)	9/11/68	»	Small. T = 15.5° C	140	154 ± 7	— 49	— 7.9			Unconfined alluvium
Theopetra	10/11/68	»	0.3 m^3 / hr. T = 14° C	190	133 ± 5	— 47	— 7.9			karstic spring
Chimadio	10/11/68	»	0.25 m^3 / hr. T = 12° C	770	146 ± 16	— 56	— 8.4			Conglomerate Oligocene
Rousson Hill	9/11/68	»	Very small; T = 15.5° C	150		— 48	— 7.9			Oligocene marls and sand.
Lazarina	10/11/68	»	0.3 m^3 / hr. T = 16.0° C	120	227 ± 9	— 52	— 8.5			Unconfined alluvium
Gomphi (B)	10/11/68	»	0.3 m^3 / hr. T = 15.0° C	133		— 50	— 8.6			Not on Fig. 1 but near Gomphi (A)
Xiloparikon	11/11/68	»	5.0 m^3 / hr. T = 12.0° C	240		— 47	— 7.9			«karstic water»
Kria Vrissi	8/ 1/69	»	T = 10.0° C	850	234 ± 11	— 51	— 8.2			» »
D - 30	28/ 5/71	drilled well 226 m	WL = + 0.79 m; alluvium; 7 waterbearing intervals; Yld. 47 m^3 / hr.	139	1.5 ± 0.4		— 8.8			

Table 4 (continued)

Sample name and (or) number	Date of sample collection	Source (and total depth if a well)	Background data	Elevation above m.s.l. (in meters)	Tritium in T.U.	D ‰ from SMOW	^{18}O ‰ from SMOW	^{13}C ‰ from PDB	^{14}C % modern	Remarks
D - 32	28/5/71	drilled well 147.5 m	WL = — 3 m ; alluvium ; 5 water-bearing intervals ; Yld. 20 m^3 / hr.	110	2.2 ± 0.5		— 7.0			
D - 33	28/5/71	drilled well 227 m	WL = — 3.2 m; alluvium; 10 water-bearing intervals ; Yld. 36 m^3 / hr.	118	2.2 ± 0.4					
D - 34	28/5/71	drilled well 227 m	WL = — 3.3 m; alluvium; 12 water-becaring intervals ; Yld. 32 m^3 / hr.	113	1.9 ± 0.4		— 9.5			
D - 43	28/5/71	drilled well 106.5 m	WL = — 0.2m; alluvium; 10 water-bearing intervals ; Yld. 120 m^3 / hr.	130	0.0 ± 0.5		— 7.8			
D - 45	3/4/71	drilled well 180 m	WL = — 4.6 m ; alluvium ; confined ; Perf. 30 - 114 m ; WB : 30 - 32 ; 40 - 46 ; 53 - 55 ; 70 - 71 ; 107 - 111. Yld. 40 m^3 / hr.	107	23.2 ± 6.1		— 7.3			
	28/5/71				11.4 ± 0.6		— 8.6			

Notes on abbreviations :

Background data

WL = water level or piezometric surface
WB = water bearing
Yld = discharge or yield
T = temperature

Remarks

ls = limestone
sand. = sandstone

TABLE 5.

Isotope data from precipitation, lysimeter and streams (Western Thessaly).

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Chrisomilia pptn.	15.10.68	Precipitation station	840	52.0		—68	—10.4
	17.12.			349.9	66.1 ± 4 2	—55	-- 8.7
	11.01.69					—85	—12.7
	7.02.					—82	—12.1
	11.03.					—68	—10.1
	12.04.				144 ± 5	—78	—11.2
	20.05.					—42	— 6.0
	13.06.					—51	— 6.8
	18.07.				320 ± 8	—46	— 5.0
	31.08.				348 ± 12	—46	— 6.6
	28.09.				143 ± 5	—40	— 7.0
	18.10.					—24	— 4.1
	30.11.					—46	— 5.7
	28.12.				53.9 ± 3.0	—58	-- 10 3
	31.01.70						
	24.02.						
	28.03.				116 ± 7		—11.3
	29.04.						
	27.06.				323 ± 13	—40	— 4.4
	11.07.						
	23.08.						
	28.09.				101 ± 7		— 7.8
	30.10.						
	26.11.						
	30.12.				59.1 ± 6 5		— 4.9
	30.01.71				57.0 ± 5.7		— 7.0
	27.02.				79.9 ± 6.8		— 9.7
	27.03.				106 ± 10		— 3.6
Meteora pptn.	15.10.68	Precipitation	596	104.3		—63	— 9.4
	22.11.						
	31.12.				60.5 ± 4.1	—49	-- 8.7
	18.01.69					—36	— 6.5
	10.02.					—64	—10.3

Table 5 (continued)

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Meteora pptn.	15.03.69	Precipitation				— 43	— 7.2
	15.04.				167 ± 7	— 86	— 12.1
	27.05.					— 29	— 4.6
	19.06.					— 22	— 3.6
	29.07.				351 ± 11	— 39	— 6.9
	31.08.				363 ± 11		
	28.09.				145 ± 9	— 42	— 8.1
	30.11.					— 20	— 5.2
	28.12.				52.3 ± 2.9	— 58	— 9.8
	31.01.70						
	24.02.						
	28.03.				128 ± 8		— 8.8
	29.04.						
	27.06.				294 ± 13		
	31.07.						
	23.08.						
	28.09.				122 ± 7		— 7.8
	30.10.						
	26.11.						
	30.12.				78.6 ± 6.8		— 7.0
	30.01.71				71.5 ± 9.1		— 8.8
	27.02.				154 ± 7		— 11.7
	27.03.				89.5 ± 6.8		— 10.3
Kephalovrisso pptn.	7.09.68	Lysimeter rain	120				
	15.10.					— 69	— 10.5
	20.11.						
	11.12.				80.8 ± 6.5	— 70	— 10.7
	16.01.69					— 51	— 8.3
	5.02.					— 52	— 8.5
	5.03.					— 65	— 9.6
	2.04.				148 ± 6	— 49	— 8.2
	16.05.					— 28	— 3.3
	11.06.					— 19	— 3.2
	5.07.				305 ± 8		

Table 5 (continued)

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Kephalovrisso pptn.	6.08.69	Lysimeter rain			288 ± 8	— 21	— 3.1
	17.09.				146 ± 5	— 38	— 6.0
	29.10.					— 10	— 2.9
	30.11.					— 46	— 7.7
	17.12.				34.7 ± 4	— 49	— 9.2
	21.01.70						
	18.02.						
	24.03.				116 ± 6		— 10.0
Kephalovrisso	20.11.68	Lysimeter percolate	120			— 43	— 7.4
	11.12.					— 46	— 7.2
	16.01.69					— 50	— 7.7
	7.02.					— 54	— 8.5
	5.03.					— 56	— 8.9
	2.04.					— 53	— 8.1
	16.05.					— 55	— 8.4
	17.09.					— 53	— 8.5
	17.12.				91.5 ± 5.1	— 45	— 8.3
	24.03.70						— 8.0
Paleomonastirion pptn.	6.03.69	Lysimeter rain	175			— 50	— 7.6
	2.04.				137 ± 5	— 48	— 8.1
	17.05.					— 31	— 3.4
	11.06.					— 22	— 3.8
	5.07.				378 ± 11		
	6.08.				371 ± 10	— 31	— 4.1
	17.09.				158 ± 9	— 36	— 5.9
	29.10.					— 10	— 3.0
	30.11.					— 58	— 7.5
	19.12.				39.0 ± 9	— 49	— 8.5
	23.01.70						
	20.02.						
	27.03.				122 ± 7		— 6.7
	13.04.						
	25.06.				341 ± 15	— 31	— 3.8

Table 5 (continued)

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Paleomonastirion	19.03.69	Lysimeter percolate	175			−44	−7.2
	2.04.					−41	−6.2
	19.12.				105 ± 6	−42	−7.0
	23.01.70						
	20.02.						
	24.03.						−9.1
Pouliana pptn.	14.12.68	Lysimeter rain	138		93.3 ± 7	−66	−11.3
	8.01.69					−71	−10.9
	8.02.					−42	−6.2
	5.03.					−63	−9.6
	2.04.				141 ± 12	−49	−8.1
	11.06.					−23	−3.6
	5.07.				306 ± 10		
	6.08.				318 ± 11		
	17.09.				143 ± 7		
	29.10.					−12	−3.0
	30.11.					−66	−8.5
	19.12.				36.7 ± 3.9	−48	−7.8
	23.01.70						
	20.02.						
	27.03.				124 ± 6		−7.6
	13.04.						
	25.06.					−27	−3.6
Pouliana	20.11.68	Lysimeter percolate	138			−50	−7.7
	11.12.					−53	−8.0
	8.01.69					−58	−8.9
	19.02.					−60	−10.0
	5.03.					−63	−10.1
	2.04.					−63	−9.7
	12.12.				86.0 ± 4.7	−58	−9.0
	23.01.70						
	27.03.						−7.5

Table 5 (continued)

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{11}O ‰ from SMOW
Sarakina pptn.	13.12.68	Lysimeter rain	170		81.7 ± 6.1	— 64	— 10.8
	15.01.69					— 52	— 8.6
	10.02.					— 41	— 5.8
	5.03.					— 64	— 9.5
	2.04.				154 ± 5	— 44	— 7.8
	17.05.					— 25	— 3.1
	11.06.					— 21	— 3.5
	5.07.				247 ± 8	— 26	— 4.1
	6.08.				377 ± 12		
	17.09.				141 ± 6		
	29.10.					— 12	— 2.6
	30.11.					— 43	— 6.0
	17.12.				40.9 ± 6 2	— 43	— 7.7
	21.01.70						
	18.02.						
	24.03.				122 ± 7		— 10.2
	24.04.						
	24.05.						
	23.06.				332 ± 17	— 14	+ 0.1
	28.07.						
	25.08.					— 6	— 2.4
	22.09.				105 ± 7		— 6.9
	27.10.				92.5 ± 7		— 6.1
	24.11.				63.4 ± 4		— 4.2
	31.12.				66.2 ± 6.1		— 4.8
	27.01.71				55.2 ± 9.3		— 5.5
	23.02.				88.9 ± 6.7		— 10.7
	30.03.				103 ± 7		— 9.1
	27.04.				209 ± 9		— 7.5
	26.05.				177 ± 7		— 6.9
	29.06.				163 ± 9		— 4.8
Sarakina	20.11.68	Lysimeter percolate	170			— 41	— 6.9
	11.12.					— 42	— 6.5
	15.01.69					— 54	— 8.8
	5.02.					— 63	— 10.1

Table 5 (continued)

Station	Date of collection	Source	Elevation in mm above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Sarakina	5.03.69	Lysimeter percolate	170			—72	—11.0
	2.04.					—52	— 7.7
	17.12.				90 ± 5	—46	— 6.7
	21.01.70						
	18.02.						
	24.03.						— 8.9
	14.04.						
	28.07.						
	22.09.				155 ± 11		— 5.8
	31.12.				154 ± 11		— 6.7
	27.01.71				213 ± 8		— 5.5
	23.02.				101 ± 6		— 5.9
	30.03.				76.3 ± 4.4		
	27.04.				65.6 ± 9.7		— 7.6
	26.05.				76.8 ± 5.4		— 7.5
	29.06.				165 ± 8		— 4.6
Portaikos	24.10.68	River			175 ± 8	—58	— 8.6
	19.11.				209 ± 8	—51	— 8.2
	18.12.					—62	— 9.6
	18.01.69				148 ± 15	—59	— 9.4
	8.02.					—57	— 8.9
	7.03.				146 ± 19	—55	— 8.7
	15.04.					—54	— 9.1
	19.05.				183 ± 14	—56	— 8.6
	16.06.					—53	— 8.7
	18.07.				171 ± 9	—54	— 8.5
	31.08.				152 ± 9	—52	— 8.8
	28.09.				192 ± 9	—56	— 8.7
	18.10.						— 8.2
	24.11.						— 8.5
	28.12.				84.3 ± 6.1		— 8.9
	29.01.70						
	24.02.						
	28.03.				113 ± 11		— 8.9
	29.04.				130 ± 8	—52	— 8.2

Table 5 (continued)

Station	Date of collection	Source	Elevation in m above s.l.	Amount pptn. mm	Tritium T. U.	D ‰ from SMOW	^{18}O ‰ from SMOW
Pamissos	24.10.68	River			199 ± 10	— 62	— 9.2
	19.11.				168 ± 9	— 49	— 7.7
	19.12.					— 63	— 8.9
	18.01.69				172 ± 19	— 62	— 9.8
	5.02.					— 57	— 9.1
	7.03.				157 ± 21	— 57	— 9.0
	15.04.					— 56	— 8.7
	19.05.				148 ± 17	— 56	— 9.1
	16.06.					— 54	— 8.6
	8.07.				167 ± 6	— 55	— 8.6
	28.09.				167 ± 6	— 52	— 8.3
	18.10.						— 7.8
	24.11.						— 8.2
	28.12.				107 ± 10		— 8.3
	29.01.70						
	24.02.						
	28.03.				125 ± 8		
	29.04.				155 ± 9	— 53	— 8.9
Pinios	24.10.68	River			192 ± 10	— 60	— 9.2
	19.11.				204 ± 10	— 57	— 8.9
	17.12.					— 61	— 9 2
	11.01.69				159 ± 18	— 63	— 9.4
	7.02.					— 62	— 9.6
	10.03.				176 ± 15	— 58	— 9.3
	12.04.					— 62	— 9.5
	20.05.				203 ± 19	— 61	— 9.4
	13.06.					— 59	— 9.1
	18 .0.				160 ± 6	— 60	— 9.3
	31.08.				180 ± 7	— 60	— 9.3
	28.09.				196 ± 9	— 55	— 9.1
	18.10.						— 8.7
	24.11.						— 9.4
	28.12.				83.6 ± 4.8		— 9.3
	31.01.70						
	24.02.						
	28.03.				115 ± 7		
	29.04.				145 ± 10	— 57	— 9.2