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Study of stable isotopes in the Kouris catchment (Cyprus) for the description of the regional groundwater flow

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Abstract

The stable isotopes of oxygen and hydrogen in groundwater and precipitation were integrated for the description of groundwater flow in the Kouris catchment (Cyprus). The catchment consists of an ophiolitic complex in the North and sediments in the South. It is characterized by strong heterogeneity of the underground media and steep slopes of the topography.

The regression line, constructed from the data of 70 rainfall samples, is described by the equation: $\delta D = 6.6\delta^{18}O + 10.9$, which shows evaporation during precipitation. The altitude gradients in the precipitation were estimated to be $-1.7\%c/100$ m for δD and $-0.27/100$ m for $\delta^{18}O$. The stable isotope analysis of 234 groundwater samples reflected fractionation due to evaporation. The origin of groundwaters in the catchment was described based on the regression equation between surface elevations and δD contents for 33 selected springs of the ophiolitic complex. It was found that the groundwaters in the ophiolitic aquifer and in the consolidated sediments originated from local recharge at high and low altitudes, respectively. On the contrary, the groundwater in the alluvium aquifer originates from the high altitudes in the ophiolitic complex. Additionally, δD data were used for the calibration of the recharge rates for a steady state groundwater flow and transport model. The resulting calibrated total steady state recharge rate was 100–130 mm per year.
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1. Introduction

Water conflicts in Cyprus have risen dramatically within the last 30 years due to growing water demands and a semi-arid climate enveloping the majority of the island. A description of the hydrogeology and calculation of groundwater balance become very urgent. Additionally, these tasks are challenging from a scientific point of view because of

the variability in time and space of climatic conditions and because of the highly heterogeneous nature of underground properties.

This paper presents application of both new and published (Jacovides, 1979) stable isotope analyses for the description of precipitation and groundwaters in the Kouris catchment (Cyprus). Stable water isotopes have been used for decades all over the world as a powerful tool in understanding groundwater flow systems, especially for highly heterogeneous regions or for those with a high role of evaporation. In Cyprus, stable isotopes analyses were performed in 1976–1979 by Jacovides (1979), encompassing the study area that included a part of the Kouris catchment. Other investigations (Verhagen et al., 1991) focused on the description of the stable isotope composition of the groundwaters of the Lefkara aquifer (chalks, marls), located approximately 30 km to the East from the Kouris catchment.

The analysis of stable isotopes in precipitation was the subject of a great number of scientific investigations (Araguas-Araguas et al., 2000; Gat, 2000, 1996; Dansgaard, 1964; Craig and Gordon, 1965; Craig et al., 1963); our research delivers new results for the precipitation in Cyprus. In the present study, we establish the regression between δD and $\delta^{18}O$ and analyze isotopic variations due to different seasons and altitudes.

Although the 'stable isotopes altitude effect' can be easily observed in precipitation, it is often different from the altitude effect in recharged water because of evaporation prior to- or during infiltration (Allison et al., 1983; Gonfiantini, 1986). In the present study, we show changes in the groundwater isotopic content due to evaporation and describe the altitude effect in recharge on the basis of observations from several springs.

The stable isotopes altitude effect in recharge has been successfully applied for the understanding of groundwater origins in mountainous basins (see as examples: Leonitiadis and Nikolaou, 1999; Christodoulou et al., 1993). In our paper, we show how this effect is used for tracing the origin of groundwater in the Kouris catchment. In parallel, the tritium and chemical data, collected in 1998–2001, were included in the study to support our hypothesis. Deuterium data were also applied for calibrating the recharge rate for the steady state groundwater flow model of the Kouris

catchment. The model was developed in previous research (Boronina et al., 2003), while in this study we use isotope data as an independent tool to estimate an optimal range for recharge.

2. Study area

The hydrogeology of the area was described in detail by Boronina et al. (2003); Jacovides (1979); Afrodisis et al. (1986); in the present paper we provide only the most essential information. The Kouris catchment is bounded on the South by the Mediterranean Sea and covers 300 km^2 on the southern side of the Troodos Massif (Fig. 1). Elevations range from sea level to 2000 m within a distance of 30 km and with local slopes of up to 70%.

Annual precipitation increases from 300 mm along the coast to nearly 1200 mm in the Troodos mountains. Annual rainfall correlates with surface elevation (average correlation coefficient for 1970–1994 was 0.93), and has been highly variable over the years. The rain falling from November to March is usually about 80% of the total annual amount.

The calculated mean annual potential evapotranspiration for the catchment for 1986–1996 varied from 1060 to 1360 mm per year for the stations at different surface elevations.

The basin is divided into two main geological zones: an ophiolitic complex in the North and an overlying sedimentary complex in the South. The ophiolites include ultramafic rocks, gabbros, sheeted dykes and pillow lavas, while the sediments are mainly chalks, marls, calcarenites and limestones (Fig. 2).

The ophiolitic rocks are highly heterogeneous because of the presence of different lithological units, which are fractured and altered at different scales. These rocks contain the major groundwater resources of Cyprus; the water is stored in the fractured and altered zones of harzburgites, dunites, gabbros and diabase dykes. The transmissivities of the gabbros and the diabase dykes vary from 2 and 703 m^2/day with a geometrical mean of 20 m^2/day according to the results of 40 pumping tests (Boronina et al., 2003). Groundwater in the ultramafic rocks, gabbros and diabases is generally of CaMg–HCO$_3$ and Na–HCO$_3$ types with low to moderate salinities
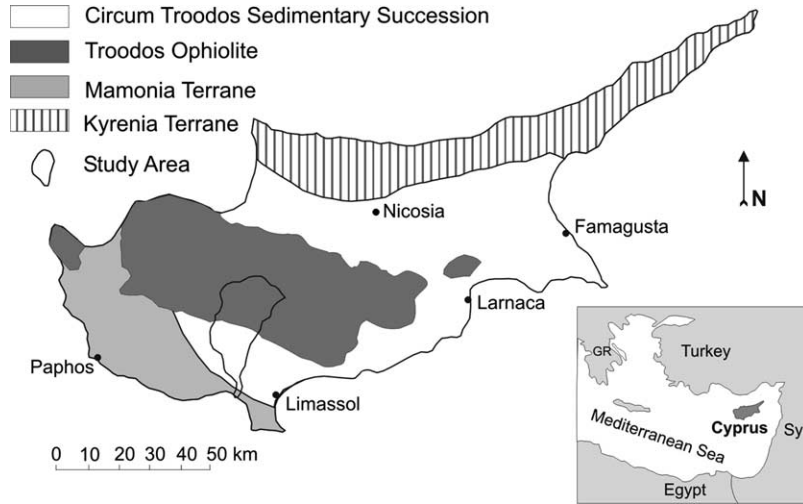
Fig. 1. Simplified geological map of Cyprus showing the location of the Kouris catchment.

(200–600 mg/l), cation and anion compositions vary considerably with the local lithology. The Pillow Lavas are considered to be generally less permeable, although local zones of high conductivity may exist there. The amounts of total dissolved solids (TDS) are higher in Pillow Lavas, than in ultramafic, plutonic and intrusive rocks (500–950 mg/l) and within the anion content SO_4 is dominating.

The sedimentary section consists of chalks, marls, calcarenites and limestones in the majority of
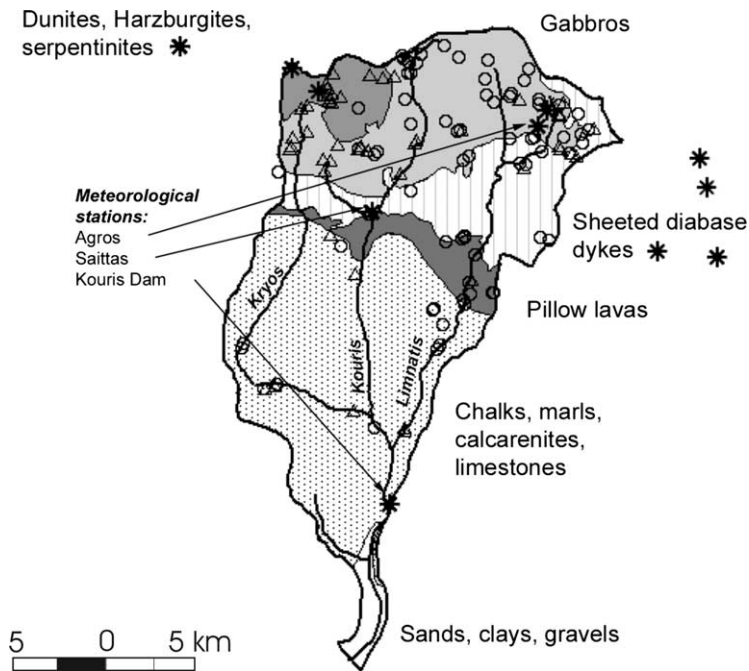

Fig. 2. Simplified geological map of the Kouris catchment; symbols show locations of sampling points for stable isotopes: circles–boreholes; triangles–springs; stars–rainfall.

the Kouris catchment (with an estimated average transmissivity of 3 m²/day), and it consists of river alluvium (sand, gravel) in the Kryos, Kouris and Limnatis valleys. Of the boreholes, drilled in this part for irrigation purposes to depths of 200–300 m, 70% stayed dry. The alluvial aquifer is narrow (sometimes less than 100 m) and discontinuous, although it contains major amounts of water in the southern part in the Kouris catchment. Groundwater in the hard sedimentary rocks are generally moderately mineralized, with salinity higher than in the ophiolites; it varies between 600 and 1600 mg/l. The waters are of Na–Ca–HCO₃–SO₄, Na–Ca–SO₄–HCO₃ or Ca–Na–HCO₃–Cl types. Groundwaters in the alluvial aquifer are less mineralized (500–600 mg/l), of the Ca–Mg–HCO₃, Mg–Ca–HCO₃ or Mg–Na–HCO₃ types.

Springs of the area originate mainly from ultramafic, plutonic and intrusive rocks (harzburgites, gabbro, sheeted dykes) in the upper part of the catchment. Only a few springs are located in the sediments, discharging water in the river valleys (if not captured). In total, 64 springs have been mapped within the catchment and there are some areas (especially in plutonic rocks) where many small springs could not be mapped separately. The Kouris catchment is drained by the rivers Kryos, Kouris and Limnatis (Fig. 2) originally discharging spring water during dry seasons, but being captured and diverted during the last summers. Kouris is the largest river in

Cyprus and has had for the last 30 years an average annual streamflow of 36 Mm³/year.

3. Analytical methods and sample locations

For the present study, during 1998–2001 we collected and analyzed 224 groundwater and precipitation samples from 114 locations for stable isotopes and 13 ³H samples. The samples were taken from groundwater (springs and boreholes), and from precipitation in different seasons and years to investigate their temporal variability (see Table 1 and Fig. 2 for details). The samples were also analyzed for chemical components. All 13 samples for ³H were taken from the sedimentary complex and Pillow Lavas.

Additionally, 67 values for stable isotopes in the Kouris catchment, reported by Jacovides (1979), and 23 isotope analysis in precipitation from Global Network of Isotopes in Precipitation database (http://isohis.iaea.org) were used.

Hydrogen and oxygen isotope ratios are expressed by δD and $\delta^{18}O$, respectively, where $\delta = [(R_{sample}/R_{standard}) - 1]1000(‰)$, R is the ratio of D/H or $^{18}O/^{16}O$ in sampled water (R_{sample}) or in Standard Mean Ocean Water ($R_{standard}$). The analytical errors (2σ) were 0.1‰ for $\delta^{18}O$, 1‰ for δD and 0.7–2.0 TU (1 TU = 0.118 Bq/l) for ³H. The stable

Table 1

Types and quantities of water samples, analyzed for stable isotopes in 1998–2001 and in 1976–1979 (Jacovides, 1979, http://isohis.iaea.org)

	1976–1979		1998–2000	
	Quantity of samples	Quantity of sampling points	Quantity of samples	Quantity of sampling points
Rainfall samples	23	2	47	6
Spring samples:				
Ophiolitic complex (ultramafic rocks, gabbros, diabase dykes)	27	15	77	31
Alluvium aquifer	–	–	14	7
Borehole samples:				
Ophiolitic complex (ultramafic rocks, gabbros, diabase dykes)	36	17	48	40
Ophiolitic complex (Pillow Lavas)	4	3	13	10
Sedimentary complex			13	10
Alluvium aquifer	–	–	12	10
Total	90	37	224	114

isotopes were measured with mass-spectrometers (type Delta-S) after equilibration with CO_2 for ^{18}O and reduction with uranium for D, respectively. The tritium determinations were performed with a liquid scintillation counter after electrolytic enrichment.

4. Results

4.1. Stable isotopes in precipitation

Fig. 3 presents δD versus $\delta^{18}O$ for 70 precipitation samples collected in the Kouris catchment, showing that the deuterium excess, defined by Dansgaard (1964) as $d = \delta D - 8\delta^{18}O$, is quite high and refers to the Mediterranean Meteoric Water Line ($d = 20$) rather than to the Global Meteoric Water Line ($d = 10$). The slope of the linear regression line

$$\delta D = 6.6\delta^{18}O + 10.9 \tag{1}$$

is smaller than the slope of the Global Meteoric Water Line ($\delta D = 8\delta^{18}O + 10$, Dansgaard, 1964; Craig and Gordon, 1965); this fact indicates evaporation during precipitation (Craig et al., 1963).

Seasonal variations of the stable isotope compositions in precipitation reached 27‰ for δD and 4.0‰ for $\delta^{18}O$ in 2000–2002 (Fig. 4). Isotopically lightest water (for all three meteostations—see Fig. 2 for

locations) precipitates during November–January and it gradually becomes heavier afterwards (Fig. 4). However, this is only a general trend; monthly values are highly scattered around it. Seasonal changes in precipitation are not clearly reflected by deuterium excess in Fig. 4.

Single rainfall events might differ in isotopic content even more; their compositions are influenced by the amount of precipitation (Fig. 5). For example, a short (1 h) rainfall on 05.11.2001 after a long dry period had deuterium content of -11.9‰. The next day longer rainfall at the same place (Agros village) already had -35.1‰ of deuterium in its hydrogen composition. The influences of rainfall amounts and history on a stable isotope composition of precipitation are explained by Gat (1996); Araguas-Araguas et al. (2000). Another reason of high variability in the isotope composition of single rainfall events is the island location of the study area. Depending on a wind speed and direction, precipitating air masses have different portions of sea moisture. This fact was illustrated by tritium studies in the Easter Mediterranean area by Gat et al. (1962).

Averaging isotope values of rainfall samples for September–April 2000/2001 result in the following Table 2, suggesting, in agreement with Verhagen et al. (1991), general altitude gradients in precipitation -1.7 ± 1.9‰/100 m for δD and -0.27 ± 0.26‰/ 100 m for $\delta^{18}O$. Deuterium excess decreases with
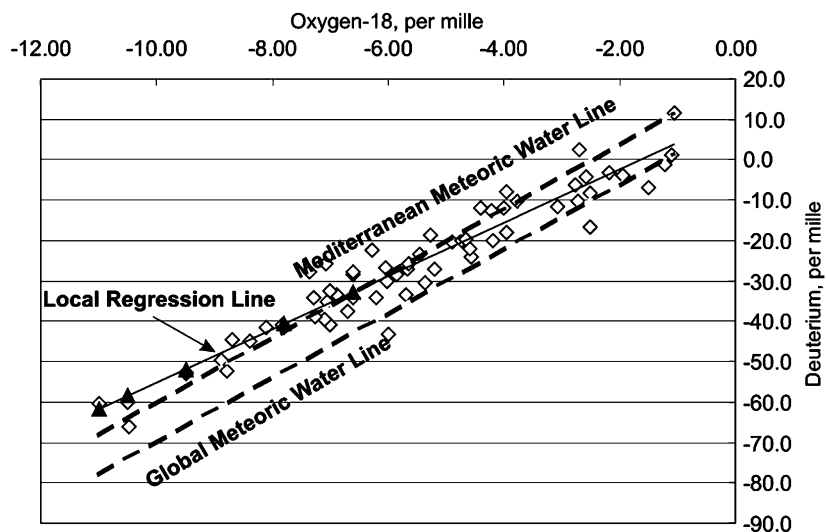

Fig. 3. δD versus $\delta^{18}O$ for 70 rainfall samples (diamonds) and five snow samples (triangles) of the Kouris catchment.
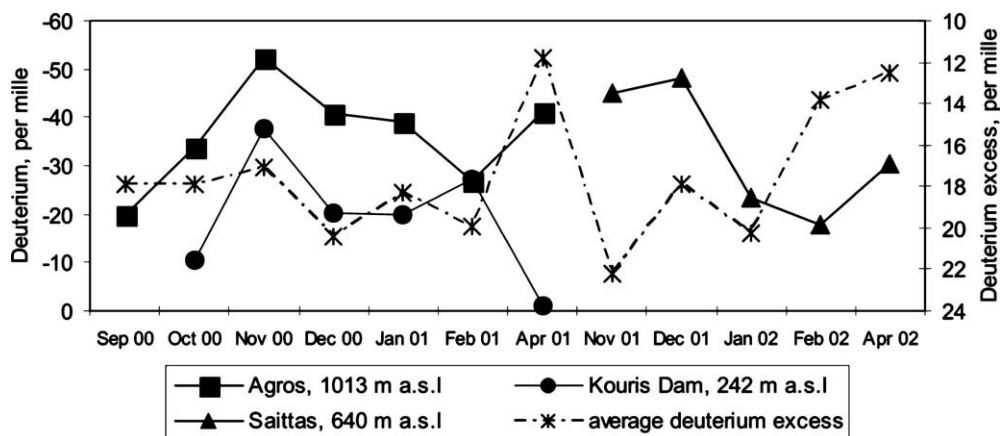
Fig. 4. Seasonal changes of δD and deuterium excess in monthly mixed rainfall samples at the meteostations in Agros (1013 m a.s.l.), Kouris Dam (242 m a.s.l.) for 2000–2001 and in Saittas (640 m a.s.l.).

decreasing altitude (Table 2), which indicates enhancing evaporation. Thus, the altitude effect in precipitation cannot be separated from the effect of evaporating of falling rain drops.

4.2. Stable isotopes in surface water

Surface water (rivers, dams) show high variability in the isotopic content (from −6.98 to −3.24 for $\delta^{18}O$ and from −39.4 to −18.2 for δD). The isotopic compositions are affected by evaporation in different seasons and mixture of baseflows from different altitudes of surface runoff. The isotope analyses of surface water are available in the Engineering

Geology library of ETH, Zürich and will be published later.

4.3. Stable isotopes in ground water

The isotopic contents of sampled groundwater vary from −7.66 to −4.61‰ for $\delta^{18}O$ and from −41.00 to −24.75‰ for δD.

Fig. 6 presents δD versus $\delta^{18}O$ for the 234 groundwater samples. Two types of groundwater can be clearly distinguished: the sedimentary complex with isotopically enriched water and the ophiolitic complex with isotopically depleted groundwater. In total, 52% of groundwater in the ophiolites
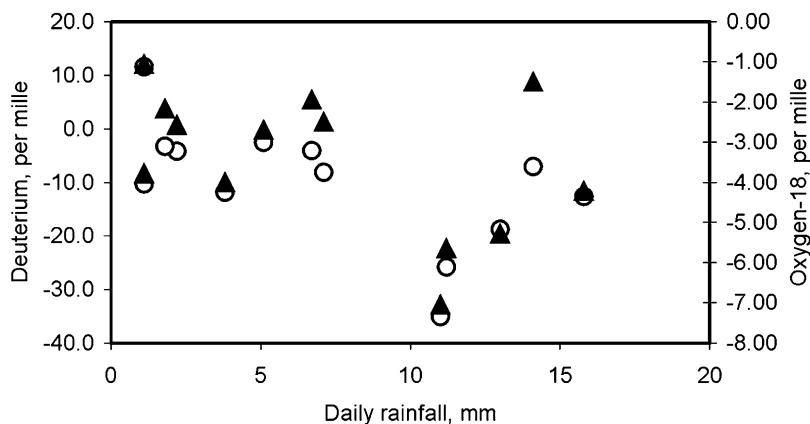

Fig. 5. Isotopic compositions (δD—circles, $\delta^{18}O$—triangles) of single rainfalls versus daily rainfall amounts (mm) at the Saittos meteorological station (640 m a.s.l.) in October–November 2001.

Table 2
Isotopic contents in rainfalls, averaged for September–April 2000/2001, at the meteorological stations in Agros (1013 m a.s.l.) and at the Kouris Dam (242 m a.s.l.)

Station	Quantity of samples	$\delta^{18}O$ (‰)	δD	Deuterium excess (‰)
Agros	7	-7.00 ± 1.30	-36.3 ± 10.5	19.7 ± 6.3
Kouris Dam	5	-4.93 ± 1.47	-23.0 ± 10.1	16.4 ± 7.4

and 10% in the sediments fall on the local regression line of precipitation, within the range of measurement uncertainties (filled symbols in Fig. 6). The rest of the samples are displaced below the local regression line around a line of a slightly smaller slope ($m = 5.9$, Fig. 6). There might be a combination of, at least, two reasons to explain this shift. First, is the evaporation prior to- or during infiltration, leading to the observed smaller slopes of the regression line. This factor may have a big influence also because of reinfiltration of isotopically enriched and fractioned water remaining after irrigation during the summers. Another probable reason is described by Allison et al. (1983), showing that the samples in the δD–$\delta^{18}O$ diagram are displaced toward a line parallel and below the local regression line because of partial evaporation from soils and dilution by subsequent recharge.

Fig. 7 shows deuterium excess ($d = \delta D - 8\delta^{18}O$) in the waters of some springs and boreholes during different seasons. No clear trend in groundwater is observed and some variations are in the range of measurement errors. This situation is probably a result of high scatter in the isotope compositions of single rainfall events over the area (see Fig. 4).

The high salinities in the groundwaters from sediments and pillow lavas cannot be explained by concentration due to only evaporation. Deuterium excess (Table 3) shows no correlation with salinities. For example wells 67/01, 68/01 and 183/01 in the sedimentary complex (Table 3), located at the same surface elevations, with 7 m difference in penetration depths (in fact, 67/01 and 68/01 were in the distance of 20 m from each other), show nearly the same isotope ratios and deuterium excess, but very different chloride contents and total salinities. A similar situation occurred in boreholes 9/5, 5/5, 10/5 (Table 3), which had the same altitude of location, $\delta^{18}O$ and δD ratios (which most probably indicates the same degree of fractionation due to evaporation), but very different salinities. The differences in TDS in those boreholes were caused by SO_4^-, while Cl^- contents were not so different; this fact also confirmed that high (compared to other groundwater in the ophiolites) salinity in Pillow Lavas was caused by
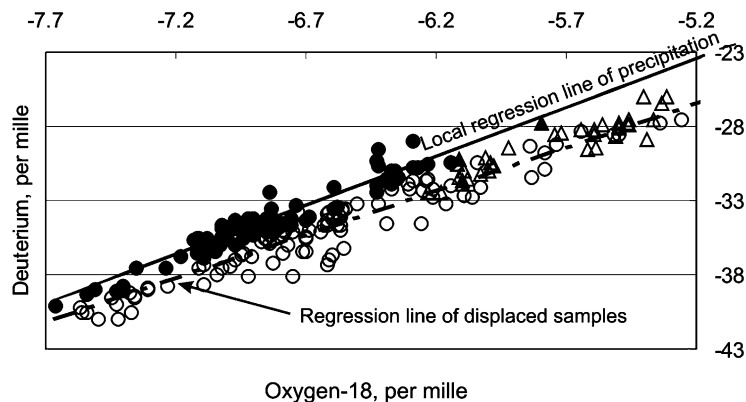
Fig. 6. Deuterium versus Oxygen-18 for 234 groundwater samples: circles–water sampled in ophiolitic complex; triangles–water, sampled in sedimentary complex; empty symbols present groundwater (in both complexes) with a shift below the Local Meteoric Water Line more than the uncertainty of the measurements.
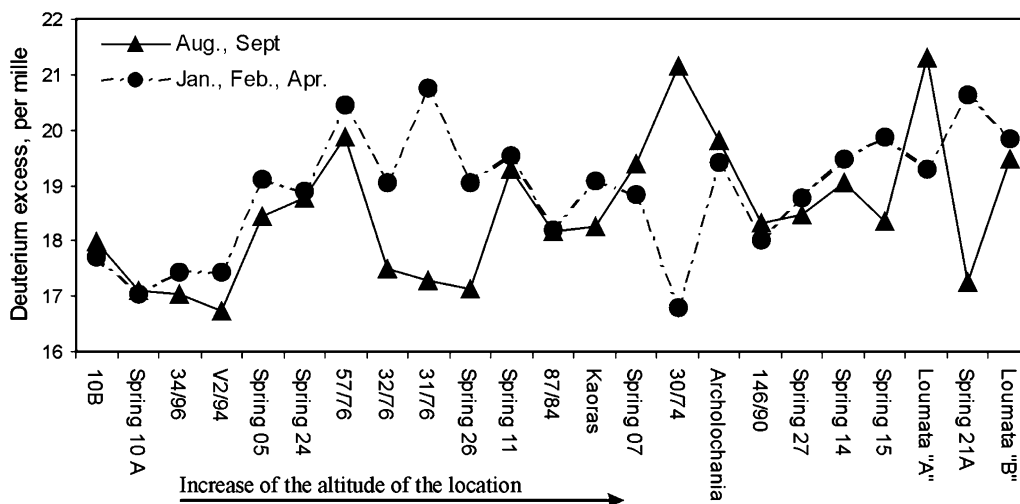
Fig. 7. Deuterium excess in the groundwaters of some springs and boreholes, illustrating seasonal changes in the aquifer.

rock dissolution rather than evaporation or transpiration.

From the ^3H content, the groundwater in the sediments and Pillow Lavas must have had residence times higher than 45 years, since it was not influenced by the anthropogenic ^3H concentrations of the 1960s (Table 3). This fact, however, can support both explanations of the increase of the salt content in the groundwater from rock dissolution or concentration due to evaporation.

Fig. 6 shows that isotope compositions of groundwater are generally different from those in precipitation, as a result of evaporation during infiltration. Thus, the altitude effect in the precipitation cannot be used for the description of groundwater origin (recharge conditions) in the Kouris catchment. Therefore, the following methodology was applied to obtain the regression between stable isotopes content of recharge and topographic elevations. In the first step, the regression equation between deuterium content of the groundwater samples and surface elevations was established; this was based on deuterium data from 33 ophiolitic springs and their average catchment altitudes,

Table 3
The examples of TDS, Cl^-, $\delta^{18}O$, ^3H contents and deuterium excess in the groundwaters of Pillow Lavas and sedimentary rocks

| Well (N)	Altitude (m)	Rock	TDS (mg/l)	Cl^- (mg/l)	$\delta^{18}O$ (‰)	δD (‰)	Deuterium excess (‰)	^3H, TU
67/01	318	Sedimentary rocks	1288	152	−5.11	−24.8	16.1	<0.8
68/01	318	Sedimentary rocks	1605	220	−5.18	−25.4	16	
183/01	318	Sedimentary rocks	1133	160	−5.05	−25.3	15.1	
8/01	378	Pillow Lavas	522	82.8	−5.14	−27.1	14	
273/01	640	Pillow Lavas	783	70.6	−5.34	−27.8	14.9	<1.2
229/01	430	Pillow Lavas	805	119	−5.59	−28.3	16.4	
54/01	457	Pillow Lavas	521	87	−5.20	−28.0	13.6	
272/01	525	Pillow Lavas	515	127	−5.50	−28.6	15.4	<1.4
9/5	495	Pillow Lavas	518	23.6	−5.27	−26.2	16	
5/5	495	Pillow Lavas	651	39.5	−5.25	−26.8	15.2	<1.8
10/5	495	Pillow Lavas	908	39.4	−5.21	−27.6	14.1	
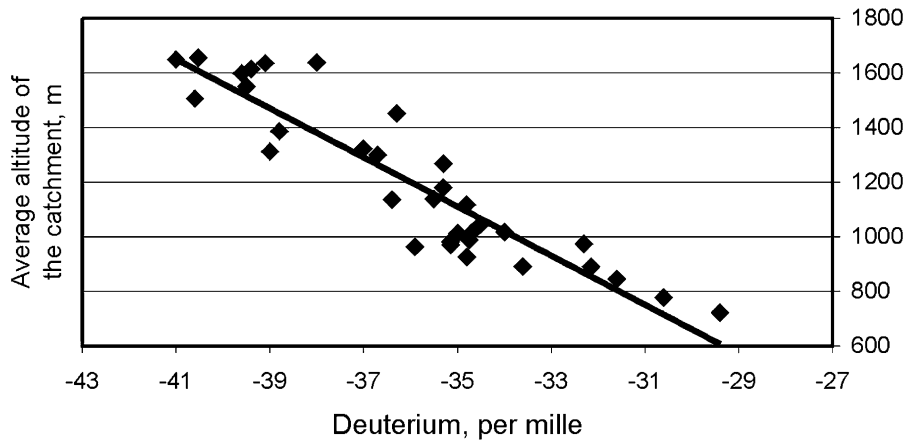
Fig. 8. Regression line between δD in 33 springs and average altitudes of their catchments.

obtained from the digital elevation model (Hall, 1998). Samples of rainy seasons were used, with the assumption that the obtained values of average surface catchments represented average altitudes of recharge. As enrichment due to evaporation generally affects the δD values less than the δ^{18}O values, the δD relationship with altitudes was used. The resulting linear regression is shown in Fig. 8 and described by the following equation

$$Z = (-2034 \pm 253) - (90 \pm 7)\delta D \qquad (2)$$

where Z is the altitude of recharge (m).

From Eq. (2) the altitudes of the recharge areas for the remaining 85 samples (excluding samples with clear evidence of evaporation) were calculated and plotted (Fig. 9) against the altitudes of the sampling points for the three sample groups (1, ophiolitic complex, excluding pillow lavas; 2, alluvium in the southern part of the catchment; 3, sedimentary rocks and pillow lavas). Although the data in Fig. 8 are highly scattered, most of the samples from ophiolites and sedimentary rocks fall between two lines: $Y = X + 253$ m and $Y = X - 253$ m (Fig. 9), where Y and X refer to altitudes of recharge and altitudes of sampling points, respectively. This fact means that within the range of accuracy of Eq. (2), the groundwaters sampled within the ophiolites and the sediments originate from altitudes not far from the altitudes of the sampling points. An exception to this rule is

the Phylagria spring, discharging water from higher altitudes (most probably, due to its location, thereby catching the river water). Other exceptions are a few groundwater samples from the ophiolites that are displaced below the line $Y = X - 253$ m, probably due to evaporation. On the contrary, the samples from the alluvium aquifer seem to systematically contain water from higher altitudes (the altitudes of the ophiolitic complex). This means that this aquifer is either fed by water from the rivers or by groundwater flowing from higher altitudes via deep fractures zones in the sedimentary aquifer. The ^{3}H and chemical data support the first hypotheses (i.e. river origin of the groundwater in the alluvium aquifer) because the ^{3}H content of water in boreholes 34/96, 10B-st, 71/92, 21/00, 22/00, 23/00, 24/00, drilled in the alluvium aquifer varied from 3.2 to 10.2 TU, which was similar to the range of ^{3}H variations observed in the rivers of the catchment. Additionally, the groundwater in the alluvial aquifer are of the Ca–Mg–HCO$_3$, Mg–Ca–HCO$_3$ or Mg–Na–HCO$_3$ types; therefore, they always contain considerable amounts of Mg^{2+} in their cation composition. As Mg^{2+} is one of the leading cations of the groundwater within the ophiolitic aquifer, it rather confirms the hypothesis that water infiltrates from the rivers that are fed by the ophiolitic springs. The opposite mechanism (water flow via fractures in the consolidated sediments) would certainly change the cation composition of the groundwater.
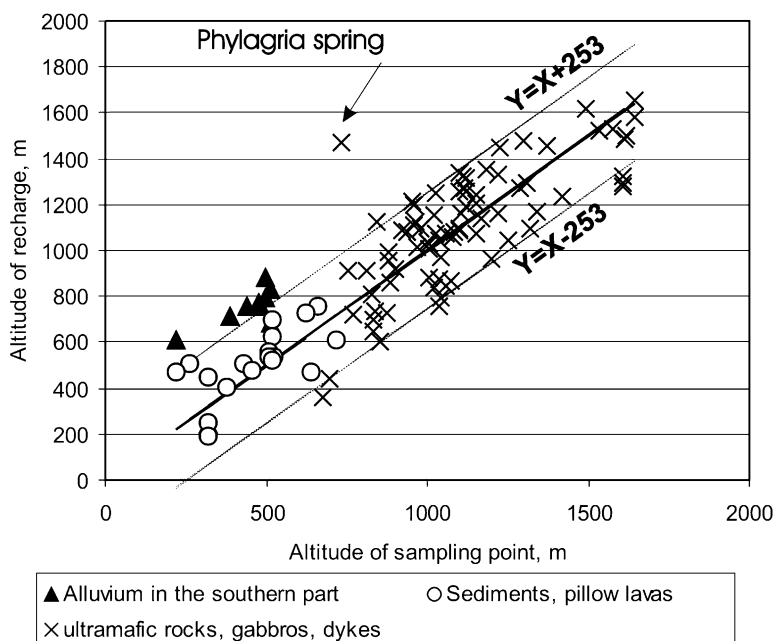
Fig. 9. Scatter diagram between altitudes of sampling points and altitudes of their recharge areas.

4.4. Calibration of the steady state groundwater model with the stable isotopes data

A steady state two-dimensional groundwater model was developed during a previous stage of the research (Boronina et al., 2003). It was based on the MODFLOW code (Harbaugh and McDonald, 1996) and had objectives and limitations discussed by Boronina et al. (2003). In spite of a good fit of observed and simulated piezometric heads, the calibration of the model based only on piezometric observations resulted in a reliable relation 'recharge rates-transmissivities' rather than in absolute values of the parameters. Further model calibration by river leakages allowed us to obtain the absolute values of the total recharge, although the quality of the data used (baseflows, separated from rivers hygrograms by the sliding interval method) was questionable that forced us to look for other tools to examine the model conclusions.

Thus, in the present study, our aim was to calibrate the absolute values of the recharge by stable isotope (δD) data. During the calibration procedure, one basic variant (the resulting model from Boronina et al. (2003)) and six variants with different absolute values

of total recharge were created. The ratios between the recharges of the different zones in every modeling variant were kept equal to those in the basic variant, while the absolute values of recharge were changed comparatively to the basic variant by factors of 0.6, 0.75, 0.9, 1.2, 1.5, and 2. Then the transmissivities of every modeled variant were changed, respectively, in order to obtain the best fit of the simulated piezo-metric heads to observed ones. Thus, seven models, calibrated only by piezometric heads, with different absolute values of recharge, were created. To develop the transport model using the code MT3D (Zheng, 1990), we had to input porosity and dispersivity values of the different lithologies, in addition to deuterium concentrations of recharge. The transport was modeled for a time long enough to reach a steady state deuterium distribution in the aquifer, which was assumed to exist in reality. Although some general values of porosities were input, they did not make a difference for a steady state transport model. The longitudinal and transverse dispersivities were assumed to be 60 and 6 m, respectively, and reflected macrodispersion in an average regional scale of 10 km (Gelhar et al., 1992). The hybrid method of charac-teristics (HMOC) was used as a solution scheme to
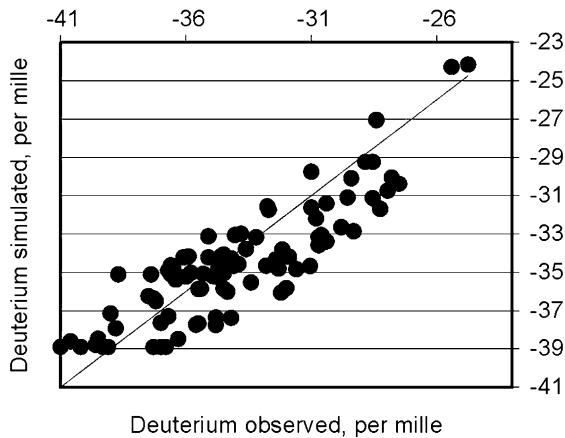
Fig. 10. Scatter diagram for 94 observed and simulated deuterium concentrations.

avoid numerical dispersion. The altitude effect of the deuterium content in the recharge was approximated by eight zones according to surface elevation, the δD concentrations of the recharge for every zone were calculated by Eq. (2). The simulated concentrations of δD were then compared with the observed ones for all modeled variants. Fig. 10 shows a scatter diagram between the 94 observed and simulated deuterium concentrations in the aquifer for the basic variant. A high scatter of the points is mainly caused by the uncertainties of input concentrations, propagated from the uncertainties of Eq. (2); an additional scatter below the line $Y=X$ is probably caused by

fractionation due to evaporation, which was not possible to model with MT3D. Fig. 11 presents the mean square root of the square deviations between observed and simulated δD values, averaged for seven locations in the Kouris catchment, and plotted against the steady state recharge (in mm). The function in Fig. 11 has a minimum between 100 and 130 mm, suggesting this range as the optimal recharge rate from the calibration with stable isotopes.

5. Discussion

In this part of the paper we will discuss reliability of the conclusions of stable isotope studies. All conclusions were made only with the sole concern of the precipitation and groundwater of the Kouris catchment. Despite the large number of surface water analyses, we did not describe them in detail, since we consider them a topic for future investigations where other approaches and types of models will be applied.

5.1. Description of stable isotopes in precipitation

In spite of the rather large quantity of precipitation samples available, this was not yet sufficient to fully understand the principles of the stable isotopes distribution in the precipitation in Cyprus; thus this part of our studies resulted only in general
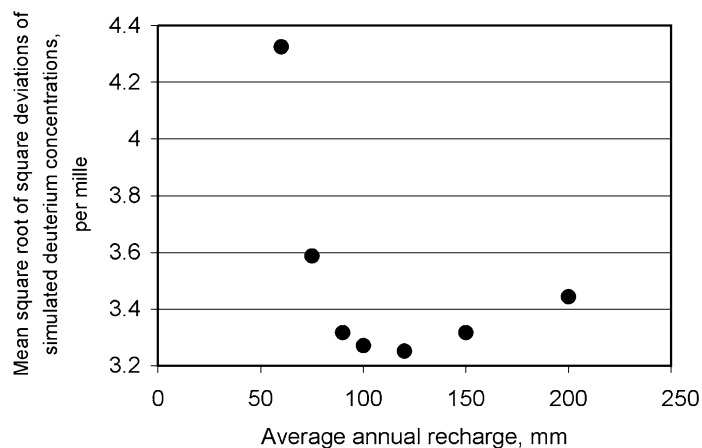

Fig. 11. The deviations between observed and simulated deuterium concentrations (axis-*Y*) for seven model variants with different annual recharge (axis-*X*).

conclusions. For example, our data cannot confirm whether or not the seasonal changes in the stable isotope contents in 2000–2002 (Fig. 4) were common for longer periods. The insularity of Cyprus brings an additional difficulty, marine air masses, that influences the stable isotope composition of the precipitation. However, in the framework of these studies it was not possible to separate this effect from the role of temperature/evaporation and altitude effect. Nevertheless, we still consider the present study as useful, since it is, to our knowledge, one of the first published description of stable isotopes in precipitation in Cyprus.

5.2. Origin of groundwater

The uncertainty related to Eq. (2) is high, most probably because of the high uncertainty in the determination of the average surface elevations of spring catchments. At the present stage, one cannot reduce this uncertainty. It then propagates through all estimates based on Eq. (2) and results in the large scatter shown in Fig. 9. That is why we can only draw comparative conclusions for the different water origins in the Kouris catchment. It seems, for example, that the groundwater in the sedimentary complex come from the local recharge, rather than from the ophiolites at higher altitudes. On the contrary, the alluvium aquifer is fed by water from the ophiolites via the rivers, and this conclusion is supported by chemical and ^{3}H data as well. These results might be more uncertain because of evaporation, which theoretically decreases the deuterium excess and makes the calculated altitudes of recharge even smaller. In that case, real altitudes of recharge might be slightly higher in the sedimentary complex and in the alluvium aquifer. However, the conclusion about the groundwater origin will still be the same as presented above.

5.3. Calibration of the numerical model

The uncertainties related to Eq. (2) propagate through the transport model as well. We consider that the deuterium concentrations imposed in the recharge have an uncertainty of ±3‰ which results in the scatter visible in Fig. 10, and this inaccuracy cannot be reduced. The mean square root of the square

deviations between 94 observed and calculated deuterium concentrations is 1.7‰, which still looked satisfactory despite the exceedance of the simulated values over the observed ones by 3–4‰ (i.e. more than the range of input uncertainty) in 10 points. The evaporation might have been the cause of these discrepancies; another possible cause is the local heterogeneities that are not included in the regional deterministic model. Thus, in Fig. 11 we would rather not look at the absolute values (which were mostly near the range of input errors) but at the type of the function and its minimum, which allowed us to make some conclusions about the range of recharge rate.

6. Conclusions

The study of oxygen and hydrogen isotopes in the precipitation and in groundwater revealed some characteristic features of the Kouris catchment. The precipitation is affected by evaporation during rainfall events. The calculated local regression line of precipitation is: $\delta D = 6.5\delta^{18}O + 10.6$. The altitude gradients in precipitation are estimated to be -1.7 ± 1.9‰/100 m for δD and -0.27 ± 0.26‰/100 m for $\delta^{18}O$. The analyses of groundwater samples showed, that during- or after infiltration evaporation occurs as well, so the altitude effect in precipitation cannot be used for the description of the groundwater origin. Thus, the altitude gradients of stable isotopes in the aquifer were obtained from the data of 33 springs in the ophiolitic complex. From the regression between deuterium data and surface elevations, the altitudes of recharge for all samples were calculated and compared to the altitudes of the sampling points. We concluded that the ophiolites, except Phylagria spring, and the sedimentary complex contain water from the local recharges at the high and low altitudes, respectively. The high salinity of the ground water in the sediments is caused by rock dissolution, rather than evaporation. On the contrary, the groundwater in the alluvium aquifer originates from the high altitudes in the ophiolitic complex. ^{3}H and chemistry data further supported this hypothesis. Additionally, deuterium data were used for the calibration of the recharge rates of a steady state groundwater flow and transport model. The resulting calibrated total steady state recharge rate is

100–130 mm per year, which is in agreement with the recharge rate obtained by the chloride mass-balance method and by the previous calibration of the numerical model with river leakages (Boronina et al., 2003).

Acknowledgments

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