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THE FUNCTION OF KARST AQUIFER TO CLEAN POLLUTED WATER IN SOUTH SUBURB OF BEIJING

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ABSTRACT

G.K.W.: human impact, lekage, pollution of water, water supply
Geogr. K. W.: China, Beijing

INTRODUCTION

The studied area is 57 km far from Beijing. With the fast development of industry in south suburb of Beijing, the Niukouyu reservoir was built up to treat the waste water from the petroleum chemical plants. As the reservoir is set on the karst polje made of Ordovician limestone and Cambrian muddy band limestone, the faults and joints are well developed. The fractured limestone causes the reservoir seriously leaking and the waste water recharges the karst aquifer by both leakage and reservoir water directly injecting into the boreholes drilled during 1973 1975. The karstic aquifer is with the high capacity to clear the polluted water entered from the reservoir. The results show that the karstic aquifer can clean 30 90% of oil, 95 99% of phenol, 85 92% of COD, and 90% of ammonia nitrogen.

The studied area is situated in the transition zone from the Tahang Mt. to north China plain. It is 57 km far from Beijing. In order to accumulate water for agricultural irrigation, the Niukouyu polje was damed to form the small reservoir is 1959. For doing oxidization treatment of waste water issued from the petroleum chemical plants, the reservoir was expanded to store 10 million m of the preliminary treated waste water. The serious leakage of the reservoir caused that it not only did not give full play of the designed efficiency, but also has polluted the karstic and Quaternary aquifers. The capacity of self-cleaning the organic contaminants in the waste water leaking into the aquifer has been made the hydrogeologists and environmental scientist to give the stressive notice.

This paper will treats on the self-cleaning capacity of the Ordovician limestone aquifer in Niukouyu area.

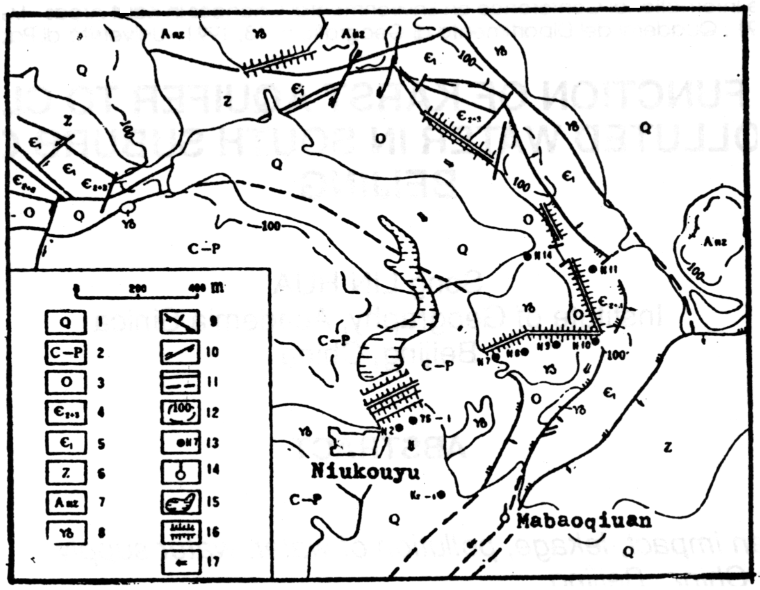

Fig. 1 Geological map of Niukouyu area, Beijing
1-Quaternary; 2-Permo-Carboniferous sandstone, breccia, Shale and Phyllite; 3-Ordovician limestone; 4-mid and upper Cambrian muddy band limestone; 5-lower Cambrian quartzite, phyllite and shale; 6-Sinian siliceous breccia and band limestone; 7-PreSinian granite-gneiss; 8-Mesozoic granodiorite; 9-Compressed fault; 10-sheared fault; 11-deduced fault; 12-topographic contour; 13-borehole and number; 14-spring; 15-reservoir; 16-dam; 17-groundwater flow direction

PHYSICAL SETTING

As the Niukouyu area is located in the transition zone from the Tahang Mountains to the north China plain. It is higher in the northwestern part and lower in the southeastern. The altitude of Niukouyu polje and plain ground surface is 54 80 m above the sea level (a.s.l.), the highest hill made of Permo-Carboniferous sandstone breccia, mudstone and phyllite is about 300 m a.s.l. in the northwest, the hills at the altitude from 100 to 160 m distribute in the Pre Sinian and lower Cambrian granite-gneiss, quartzite, sandstone, shale and phyllite in the east region (Fig. 1). The Niukouyu polje is developed on the contact between Permo-Carboniferous sandstone and shale and the Ordovician limestone (Fang and Song, 1990).

The studied area is in the temperate and semihumid monsoon climatic zone, the annual mean temperature is 11.6 °C, the highest monthly average temperature in July reaches up to 26 °C and the lowest in January is -5.4 °C. The yearly mean ground temperature is 14.6 °C. The annual average precipitation 607 mm , it is homogeneous distribution. It was only 382 mm in 1984, but 180.3 mm in August, that was about 46% of the annual rainfall. The evaporation was 958-1050 mm on the water surface (Song et al., 1986).

The PreSinian granite-gneiss rocks distribute in the eastern part, the Sinian siliceous breccia and bandy limestone occupies in the northeast region and the south block of Fangshan-Babaoshan fault in the southeastern. The lower Cambrian quartzite and

Table 1 The chemical compositions of Ordovician limestones in Niukouyu reservoir area, Beijing

Chemical Compositions (%)

No.	Lithology	CaO	MgO	SiO_4	Fe_2O_3	Al_2O_3	Loss	CaO/MgO
1	Grey black dense limestone	47.95	2.21	6.17	0.83	1.47	39.96	21.7
2	Withe coase-crystal marble	52.56	1.03	3.08	0.60	0.46	41.66	51.0
3	Grey black coase crystal limestone	44.10	2.53 11.21	0.60	2.87	36.74	17.4	
4	Grey black thick limestone	51.8	0.81	3.65	0.72	0.84	41.38	64.0
5	Grey black coase crystal limestone	48.00	3.25	7.94	0.19	0.36	39.54	14.8
6	Grey white coase crystal limestone	52.62	1.17	2.65	0.52	0.56	41.98	45.0
7	Grey black fine crystal limestone	49.52	0.60	6.80	0.49	1.69	39.50	82.5

dark phyllite occurs in the eastern terrain which constitutes the eastern boundary of the karstic aquifer. Ordovician pure and thick limestone and mid and upper Cambrian muddy band limestone which is the basic material of karst aquifer in the study area. The limestones distributes in the central region which is limited by the arch faults F1 and F2 from north to south. Table 1 gives the chemical compositions of Ordovician limestones, the contents of CaO is 44.00-52.60%, ratios of CaO/MgO is averaged as 47.9, the highest value is 98.8, the loss amount by burn is 36.74-41.98%. While the Permo-Carboniferous shale, sandstone and quartzite distribute in the western and south regions of the studied area. As the Yenshan Tectonic Movement, the granite-gneiss erustrated into the sedimentary rocks several times in the south and eastern region. Quaternary sediments including the residual materials, flooded and fluvial sediments cover on the older stratygraphy.

There are 3 arch faults developed in the studied area from northwest to east and southeast and through whole study area. As the rotational geoforces, the lateral faults also were produced though they are not so large.

The main directions of joints are N60-70°E and N45-80°W. The density of joints N70°E is 36 Joints/m and 29 joints/0.8 m for the joints N60°W. The width of joints gradually decrease from the ground surface downwards. The quarries and 178 shallow boreholes show that the joints well developed only 0-10 m below the limestone surface.

The shallow opened joints are filled with red clay and soil.

The joints surface take the shape of the solutional waves and black residual dissolved silt sheets about 1-3 mm thick remained on the joint surface of limestone. According to the study of paleo-environment of karst development in Zhoukodien, the karst geomorphology was strongly developed in the Neocene with warm and humid climate conditions and warm and more rainfall in the early Pleistocene, later the climate became cool and dried. Therefore the Niukouyu polje might be formed in the Neocene and early Pleistocene (Fang and Song, 1990).

HYDROGEOLOGICAL FEATURES

The main karst aquifer is made of the Ordovician pure and thick limestone and mid-upper Cambrian muddy band limestone which distribute in the central region arrounded by Cambrian quartzite and phyllite, Sinian siliceous breccia and band limestone, Permo-Carboniferous sandstone and shale and Mesozoic granite. The groundwater of karst aquifer is recharged from the noncarbonates. Since the Niukouyu reservoir was built the leakage and pouring water from the reservoir has become the most important source of the groundwater. The mixing water of natural water with waste water greatly influence on the characteristics and development of karst aquifer.

In order to study the features of karst aquifer, the methods of hydrological observation, hydrogeological tests, environmental isotope hydrological analysis (Song et al., 1987) and the organic contaminant contents study and so on have been employed.

The Ordovician limestone is buried 154 m below the groundsurface and above it is the sandstone, quartzite, phyllite and shale nearby the borehole 75-1. The pumping test got the results that when the abstract depth 20 m, the borehole 75-1 was very fast to be dried out. When the water level of the reservoir is higher than 76.55 m a.s.l., it begins to overflow, the discharge is only 0.3 l/s. When the reservoir water level is at 80.65 m a.s.l., the flow in borehole N2 which was insetted into Permo-Carboniferous sandstone and shale is 0.43 l/s. The results suggested that the Ordovician limestone with lower transmission in the depth 154 m below the groundsurface.

N8 and N9 boreholes are drilled in the Ordovician limestone interoccured with granites, the total length of granite occupies 64 and 78% of the total length of rock cores in N8 and N9, respectively. The absorption coefficient from 54.0 m to 59.2 m a.s.l of N8 in the compressing test is 2.15 l/min.m and 0.12 l/min.m from 54.00 m to 49.56 m a.s.l, it is less than 0.16 l/min.m below 49 m a.s.l. The specific release capacity of N9 in the pumping tests is 0.26-0.43 l/s.m and the specific absorption is less than 0.12 l/min.m during the compressing tests.

Interoccurence of the Ordovician limestone and granite above 31.75 m a.s.l. The specific absorption of compressing test in section of 59.43-35.35 m is higher than 3 l/min.m and release capacity during pumping tests is 2.97 l/s.m and the transmission 83 m/d. So high absorption and release coefficients may be caused by the fault F1 as the limestone faultily contacting with sandstone and shale at the altitude of 31.75 m. The terrain between N7 and N9 boreholes, the granite broadly distribute and the red residual soil and clay cover on the older rocks that will make the terrain with low transmission or say that constitues the subsurface dam.

N10 borehole is located on the contacts of Ordovician limestone with mid-upper Cambrian quartzite and phyllite, the solutional fissures and small conduits are well developed in the limestone especially in the section from 51.04 m to 48.74 m a.s.l that is equal to the water level fluctuations of Mabaoqiuan spring. The specific release capacity of N10 at that section is 6.42 l/s.m, the absorption coefficient for the compressed test is 58.10 l/min.m and the transmission of limestone aquifer reaches upto 248 m/d.

The boreholes N11, N12 and N13 are situated on the contact zone between the mid-upper Cambrian quartzite and phyllite. The hydrogeological tests show that the specific release and absorption capacity are very low. For example, the specific release and capacity of N12 is 2.73 l/s.m at 8 m of abstract depth and less than 0.158 l/s.m at the drawing depth of 18.85 m at borehole N13.

The facts mentioned above suggested the Ordovician and Cambrian limestone aquifer is sorrounded by the impermeable rocks except the corridor from N14 to N10

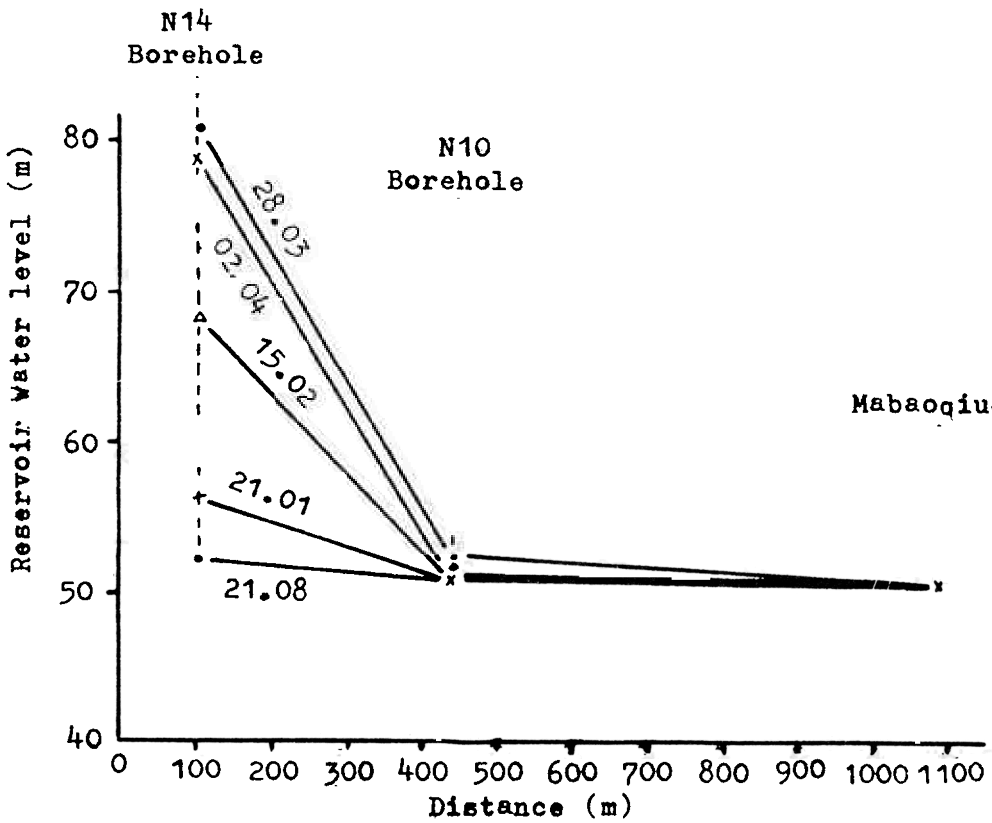

Fig. 2 Hydraulic gradients from N14 to N10 and Mabaoqiuan spring.

and Mabaoqiuan spring that makes the aquifer in the semi-closed environment.

When the reservoir water level is higher than 79.52 m a.s.l., the cana collecting the seepage water at the foot of No. 4 supplementary dam began to appear. When the reservoir water level reaches 80.80 m, the flowing water at the collecting canal is 1.405 l/s and 0.761 l/s at the fault contact between muddy band limestone and quartzite and phyllite under the hydraulic gradient of 100 ‰ (reservoir water level at 80.80 m and seepage zone at the altitude of 69.5 m a.s.l.).

Borehole N14 is drilled in the Ordovician limestone aquifer, when the reservoir water level is rising upto 75.55 m from 74.20 m, the water table in N14 borehole increases from 54.83 m to 68.40 m. At the same time, it is only increased 0.34 m from 50.64 m to 50.98 m in borehole N10. When the water level of the reservoir reaches up to 77.90 m, the reservoir water directly flows into N14 through the skew holes of the case, but the water level in N10 is only 51.16 m.

Fig. 2 gives the idea of hydraulic gradients from N14 to N10 and Mabaoqiuan spring. The hydraulic gradients from N14 to N10 varies in the range of 3.99 - 83.40‰, the average 43.42 ‰, the mean gradient from N10 to Mabaqiuan is 1.19 ‰, the variation of 0.29-3.15 ‰ .

The hydraulic gradient from N14 to N11 is yearly averaged as 49.95 ‰, the variation of 4.41 - 95.4 ‰, it is little higher than that from N14 to N10. The gradient from N11 to N10 is 15.56 ‰, the variation of 1.23-31.8 ‰, as the water flows along the influence zone of F2 fault.

Fig. 3 describes the relationship between the water level of reservoir and the

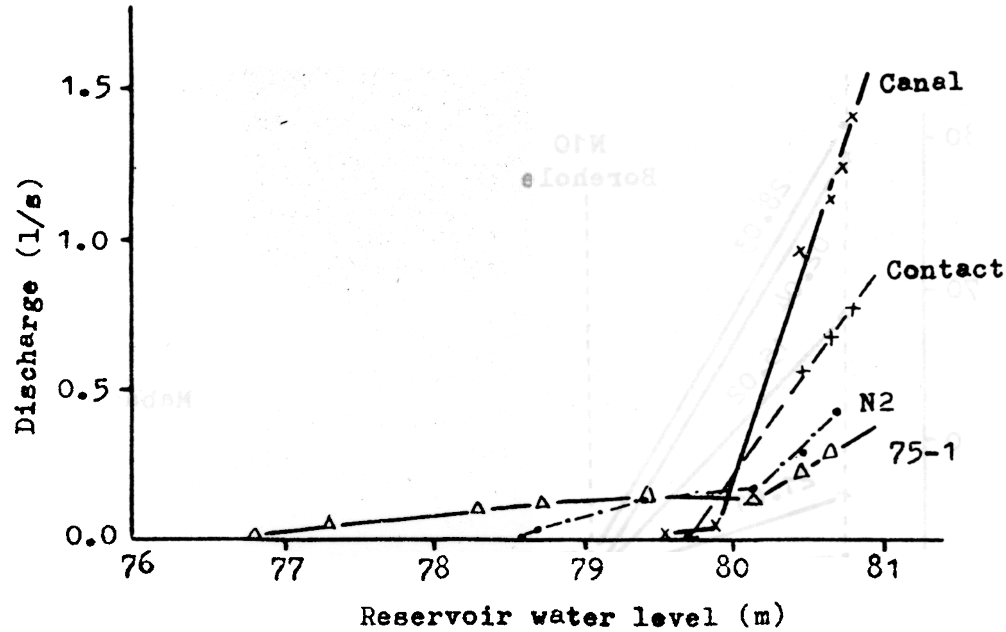

Fig. 3 Relationship between discharge of 75-1 borehole, N2 borehole, contact of limestone with sandstone and shale and seepage water at foot of No.2 supplement dam and reservoir water level.

seepage flow by the collecting water canal at the foot of No. 4 supplementary dam and at the fault contact between the muddy band limestone and sandstone and shale. Fig.3 suggested that the flowing water is increasing with the reservoir water level, but there is a knick point about 79.8 m a.s.l., the seepage is slowly increased with the reservoir water level, but when it is higher than 79.86 m, the seepage is quickly increased with the water level. From the observation from the quarries in the reservoir, the water flows out from the fissures. Thus the water in the karstic aquifer flows following the lamination law. The karstic aquifer is characterized with the fracture and conduit aquifers.

SELF-CLEANING CAPACITY OF KARSTIC AQUIFER

The Niukouyu reservoir is applied as the accumulation for the treated water from the sewage works. But some times, the water from the project still contain high contents of the organic contaminants from the petroleum chemical plants. It will pollute the karstic ground water and Quaternary aquifer in the studied area and nearby.

Table 2 gives the contents of phenol and arena in the reservoir water, groundwater in N10 borehole and Mabaoqiuan spring. In 1974, the water samples were taken from Niukouyu reservoir, N10 borehole and Mabaoqiuan spring from January to October. Though the waste water from the petroleum chemical plants was treated while when some events happened, the waste water is very difficult to be

Table 2 gives the contents of phenol and arena in the reservoir water, groundwater in N10 borehole and Mabaoqiuan spring. In 1974,

No.	item	J	F	M	A	M	J	J	A	S	O
1	.			6.75	0.075	0.025	0.015	1.82	0.027	0.019	0.023
1	Are.	1.80		5.20	3.36	1.84	2.0	3.80	2.32	1.70	1.20
2	phe.			0.0058	0.004	0.0036	0.007	0.0003	0.001	0.0009	0.0019
2	Are.			0.24	2.72	0.52	0.108	0.036	0.112	0.20	0.24
	phe.	0.0142		0.012	0.0074	0.0044	0.0017	0.0009	0.0003	0.0009	0.0011
	Are.	0.24		0.36		0.48	0.14	0.8	0.24	1.0	0.013

Note : No. 1, Niukouyu reservoir
No. 2, N10 borehole ground water
No. 3, Mabaoqiuan spring

treated completely by the works as so much water is suddenly delivered into. Therefore the reservoir will contain the waste water with high contents of organic contaminants. From table 2. we shall see that there is no regularity for the contaminants in the reservoir water, however it is very clear that the contaminants contents in the borehole N10 and Mabaoqiuan spring are lower in the period from July to October. At the time the reservoir water level kept the lower position about 70 m a.s.l., the input of waste water was only equal to the output of reservoir water. From July to September, it is the rainy season and meteoric water infiltrates down to limestone aquifer to feed the ground water, the low contents of phenol and arena in Mabaoqiuan spring and ground water in N10 may be the fresh water diluted and polluted ground water, so it makes the contaminant contents lower than the usual values from the self-cleaning of the karstic aquifer.

To study leakage problem of the reservoir, the contaminants in the reservoir, N2 borehole, the canal collecting the seepage water at the foot of No.4 supplement dam of

Table 3 The mean contents of phenol, oil, COD and ammonia nitrogen during March 25-April 10, 1986 (mg/l)

Objects	Niukouyu reservoir	N2 borehole	At foot of No.4 supplement dam	Mabaoqiuan spring
pH	7.55	7.03	7.22	7.37
Electric conductivity us/cm	600	310	433	436
Oil Cont.	4.97	0.082	0.195	0.510
Oil R.R (%)	99.30	96.49	90.81	
Phenol Cont.	9.79	0.0081	0.0175	0.045
Phenol R.R (%)		99.98	99.83	99.49
COD Cont.	409.5	27.7	60.36	52.83
COD R.R (%)		93.22	85.35	87.06
Ammonia Cont.	11.4	0.40	0.336	0.090
Nitrogen R.R (%)		96.54	97.07	91.80

Note:R.R (%) Reduce rate in %;
Cont. Content in mg/l

Niukouyu reservoir and Mabaoqiuan spring were sampled each day during March 25-April 10, 1986. the results are given in table 3.

March 25, 1986, when the reservoir water level arriving by 78.72 m a.s.l, the water was flowing out from the borehole N2 in sandstone and shale and seeping out at the foot of No.4 supplement dam of Niukouyu reservoir. The contaminants were monitored from March 25, 1986. As the water level rising by 77.90 m, the water was directly pouring into the water level rising by 77.90 m, the water was directly pouring into N14 borehole to feed the karstic aquifer, so we replaced the reservoir water samples to N14 borehole water and did not take the water samples from N10 borehole.

Table 3 shows the oil content Niukouyu reservoir is 4.97 mg/l. The oil contents of the water overflowing from borehole, seepage water at the foot of No.4 supplement dam and Mabaoqiuan spring are 0.082, 0.219 and 0.623 mg/l, respectively. The sandstone and shale of Permo-Carboniferous Periods may strongly absorb oil in the waste water, it decreased average 98.30% of the oil in the input water from reservoir, but the fissure medium of Ordovician pure thick limestone and Cambrian muddy band limestone may absorb ≥ 5.24% of the oil, while the fissure and conduit aquifer only cleaned 86.31% of oil in the ground water from N14 throght N10 to Mabaoqiuan spring.

The mean chemical oxygen demand (COD) is defined as the total requiring amount of oxygen to oxidize the organic matter to CO_2, H_2O, P_2O_5 and SO_2 (transfering N-organic matter to NH_4) made of C, H, S, P and other elements except nitrogen. Because the waste water was issued from the petroleum chemical plants, the water contains too much organic materials through it was treated, so the COD value was so high, the average content 409.5 mg/l in Niukouyu reservoir. Through the oxidization of sandstone and shale and limestone aquifer on the seepage way, the contents were reduced down to 27.7, 60.36 and 52.83 mg/l, respectively in N2 borehole, seepage water at the foot of No.4 supplement dam and Mabaoqiuan spring, correspondently decreased 93.22, 85.35 and 87.06% of the requirement in the reservoir water.

Phenol is one of the principal compounds in the petroleum chemical water. 9.97 mg/l of phenol in the reservoir water was recorded during March 25-April 10, 1986. It was greatly decreased by the karstic aquifer and noncarbonate aquifer, the contents in N2 borehole, the seepage water and Mabaoqiuan spring were 0.0081, 0.0175 and 0.045 mg/l which were 0.05, 0.17 and 0.51% of the concentrations in the reservoir water. The ammonia nitrogen in the reservoir was averaged as 11.4 mg/l, 0.40, 0.336 and 0.90 mg/l of ammonia nitrogen in sample site 1, 2 and 3 respectively. 96.54, 97.09 and 91.80% of the input contents from the reservoir have been decreased.

SHORT DISCUSSION AND CONCLUSION

The short research periods in Niukouyu area, the results have demonstrated the karstic aquifer may clean the organism contaminants in the waste water. The self-clean capacity of limestone karstic aquifer was quite different according to the properties of the aquifer medium. the capacity of diffuse flow is stronger than that of conduit aquifer in which the ground water runs very fast and is just little time to make the physical and chemical reaction between the waste water and limestone and oxygen in the water or dissolving in the water from the fissure and conduit air. Through the mechanism of karst aquifer with so high self-cleaning capacity against organic materials in the wastewater from the petroleum chemical plants have not been deeply studied yet, it is very clear that they may decrease over 85% of organic contaminants even 99% of phenol.

Though the karstic aquifer may hold high capacity to clean the organic materials in the waste water from the petroleum chemical plants like in Niukouyu area, it is still very clear that the remaince of the organic matters in the water are greatly exceed the standard for the water supply, for example, the maximum content of phenol in the water supply is limited in 0.002 mg/l by the World Health Organization. In fact, the Quaternary aquifer down the studied are has been polluted by the karstic aquifer in the research region. The groundwater only is used as the irrigation and cooling water for the factories.

REFERENCES

FANG JUINFU and SONG LINHUA (1990) - The characteristics of Karst polje and their hydrogeological significance in Zhoukoudian area, Beijing. In Research of karst geomorphology and speleology (Ed. Song Linhua et al), Science Press, Beijing. pp 197-203.

SONG LINHUA et al.(1986) - Study on the leakage of Niukouyu reservoir (unpublished), technical report.

SONG LINHUA, FANG JUINFU, ZHANG ZHONGLU and WANG CHANGFU (1987) - Study of stable isotope hydrology in Niukouyu area, Beijing. Carsologica Sinica. Vol. 6, pp93-100.

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NEW TRACING EXPERIENCE IN THE SEBES MOUNTAINS - ROMANIA.

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ABSTRACT

G.K.W.: Hydrology, resources, tracing experiments
Geogr. K.W.: Romania, Sebes Mountains

A tracing experience with In - EDTA, which prove the underground connection between Ponorici II Sinkhole and Sipot springs, correlated with discharge-precipitation diagrams and hydrochemical data, complete the image of an important karst water reservoir.

The area is part of the Southern Carpathians and is situated on the western side of the Sureanu montane unit (fig 1).

In the area there are Paleozoic, Mesozoic, Tertiary and Quaternary sedimentary formations that have metamorphic rocks in the basement, which belong to the Getic Nappe.

In the Mesozoic deposits several Jurassic and Cretaceous formations have been separated. We shall present only the carbonate formations.

Limny sandstones, bioclastic limestones, marly limestones and biomicritic rocks (Aalenian - Lower Oxfordian).

This is a predominantly carbonate sequence about 70 m wide, unconformably disposed over the older sedimentary formations and the metamorphic basement of the area (pop, 1985).

Micritic, biomicritic,pelloid and nodular limestones, biolitic limestones (Upper Oxfordian - Tithonian).

These deposits are 100 - 150 m wide and appear on two distinct facies; a) basin - like one represented mainly by micrites and biomicrites and b) a reefal one, represented by red micritic limestones probably corresponding to the Tithonian, which cover the 50-70 m wide reefal massifs limestones. In the lower part these limestones are locally dolomitized.

Urgonian limestones (Upper Jurassic - Lower Aptian).

The metamorphic basement and sedimentary formations are unconformably overlain by an important mass of about 300 m wide limestones. These limestones are largely spread in the area and present a wide variety of carbonate structures bearing biomicrites, biopelmicritites, pelmicrites and their sparitic correspondents.

The bauxite complex (Upper Aptian - Albian).

The Upper Jurassic Lower Cretaceous limestones are discontinuously overlain by the bauxite complex, that appear in the form of some bodies of different dimensions,

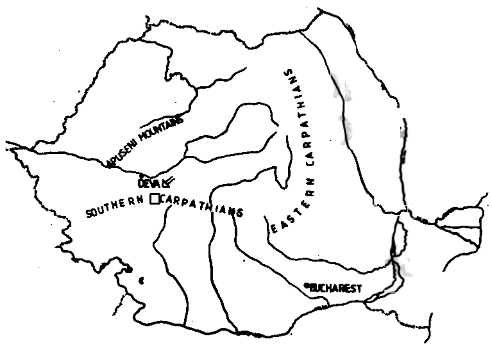


Fig. 1

varying from insignificant appearances to 800/500 m, over 20 m wide lenses.

The bauxite complex is made up of a complex association of hematitic clays and hematitic clay siltites.

GROUNDWATERS IN KARSTIFIED FISSURED ROCKS

About 500 m is the total width of the aquifers situated in Mesozoic limestones.

The crystalline formation (plagiogneisses, gneisses, micaschists)of Precambrian age constitute the impermeable basement for the karstic aquifers in the area.

The Strei valley penetrated the limestone mass, deepening to 400 - 500 m, generating two distinct plateaus: Ponorici Cioclovina - Ohaba Ponor on the right side and Bojita - Tecuri, on the left side. The plateaus margins are made up of vertical cliffs, where the karst phenomena are represented by fossil caves and rockslides (fig.2).

THE PONORICI CIOCLOVINA - OHABA PONOR KARSTIC PLATEAU

The ground waters in this area lie in Aalenian-Lower Oxfordian, Upper Oxfordian - Tithonic and Upper Jurassic - Lower Aptian deposits.

The Upper Jurassic - Lower Aptian limestones show the greatest extent, covering 45 Km^2.

In this area 21 swallets and 14 karstic springs have been pointed out.

The most important discharges are those of the swallets whose waters gather from crystalline formations and vary between 5 - 50 l/s. The waters of the other swallets collected from Mesozoic non-karstified formations, always present discharges under 1 l/s, with two exceptions, the Scarisoara II swallets (1 - 2 l/s)and the Lunca Ohabei swallet (3 - 5 l/s). All the losses are in the Upper Jurassic - Lower Aptian formations and range between altitudes of 800 and 1000 m, are disposed.

THE PONORICI - CIOCLOVINA CU APA KARSTIC SYSTEM

Situated in the northern part of the limestone plateau, the Ponorici - Cioclovina karstic system collect the waters from a surface about 10 km^2.

This hydrogeological basin was partially outline by the surveying activities done in Ponorici Cioclovina cu Apa, Cioclovina Uscata (1) and Valea Stinii caves, later the groundflow image being completed with dye-tracing experiences.

The cave is the third penetration in Romania, whose passages are disposed on 7 km length and 170 m vertical development.

The second important cavity in the system is the Valea Stinii cave, which is 1400 m long. The underground connection between the two caves has been proved by dye-tracing experience. Rhodamine B injected at the downstream end of the Valea Stinii cave has been intercepted in the right main side tributary of the Cioclovina cu Apa cave.

Situated above the main outlet, the third important cave which belong to the system is Cioclovina Uscata Cave, situated above the main outlet. Recently in the cave a small stream has been checked with tracers, but the results were not conclusive, although the surveying data of the underground cavities pointed out their belonging to the same system.

Other two swallets, Trei Piraie (3) and Robului (4) are situated near the Cioclovina resurgence and it is supposed that their waters supply the same collector. It is supposed the same thing about the underground river intercepted in the Triscioare pothole, placed near the above mentioned swallets as well as with the recently discovered swallet formed at the bottom of a suspended doline (2), disposed on the left side of the Ponorolui valley.

The minimum average discharge of the swallets which supply the system is about 30 l/s and represents 40 % of the multi-yearly average discharge rate of the Cioclovina spring (125.1 l/s).

THE SURA MARE KARSTIC SYSTEM

The Sura Mare cave resurgence is situated at the bases of the Ponorici Ohaba Ponor karstic plateau. The main flowing direction, tectonically controlled by a NE - SW fracture contoured a subterranean cavity 6700 m long and + 405 m vertical development. The upstream end of the cave is lying at a 20 m dislevelment under the Fundatura Ponorului sinkhole. The subterranean connection between the main swallet of the system and the resurgence, determined in the past by studies regarding the pulses discharges variations at water inlet-outlet, is now confirmed by the cave survey.

A gauging station situated downstream the confluence between Sura Mare and Cocolbea resurgences recorded a mean annual runoff of 365 l/s, corresponding to a total annual precipitation of 487.9 mm. (fig. 5)

The Sura Mare cave passages, partially have crystalline impermeable rocks on the floor , the flood hydrograph being of a vadose cave stream and tend to be peacked and similar to a surface river.

The storage is strongly influenced by the proportion of the rainfall input that runs off and the lag between the input event and the output response is very short.

The fact that the Fundatura Hobenilor Pothole (6) which is a water inlet belongs to the system was proved by M. Dumitrescu (1967), by a tracing experience with Fluorescein. This test was repeated in 1987 by G. Ponta , with 3.5 kg of Rhodamine B that did not appear in the Sura Mare outlet.

The second experience with tracers was carried out in the underground stream of Dosul Lacsorului pothole. The tracer was intercepted in a sidestream of the Sura Mare cave.

The average discharge of the cave is 150 l/s, while the total average discharge of the swallets id 53 l/s, which represents a percentage of 35 % . Very close to the Sura Mare resurgence it is to notice the presence of a spring on the left side (Gaura Frintoanei) and three springs on the right side. The Gaura Frintoanei cave is an outlet cavity 1200 m long, with average discharge of 2 l/s.

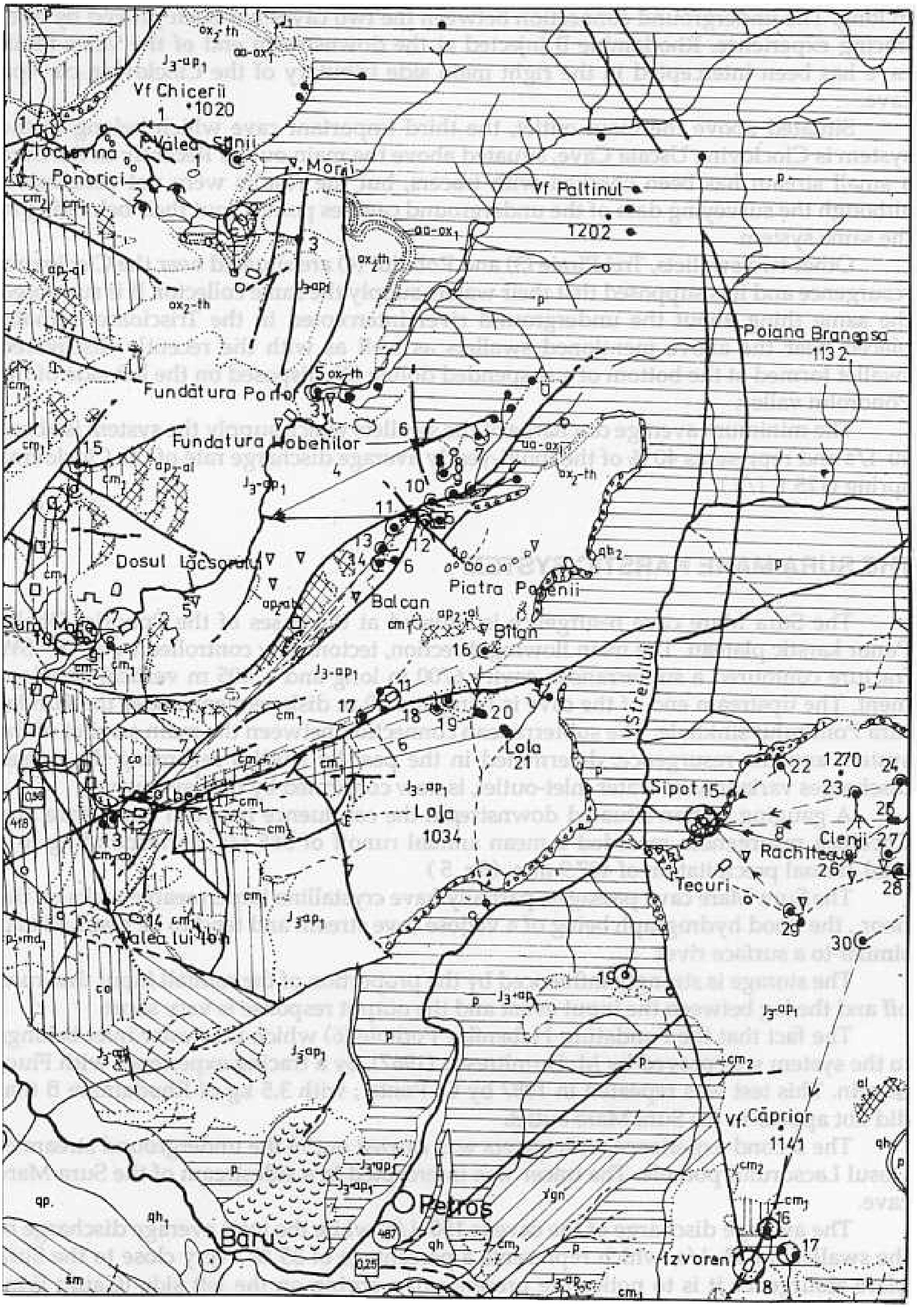
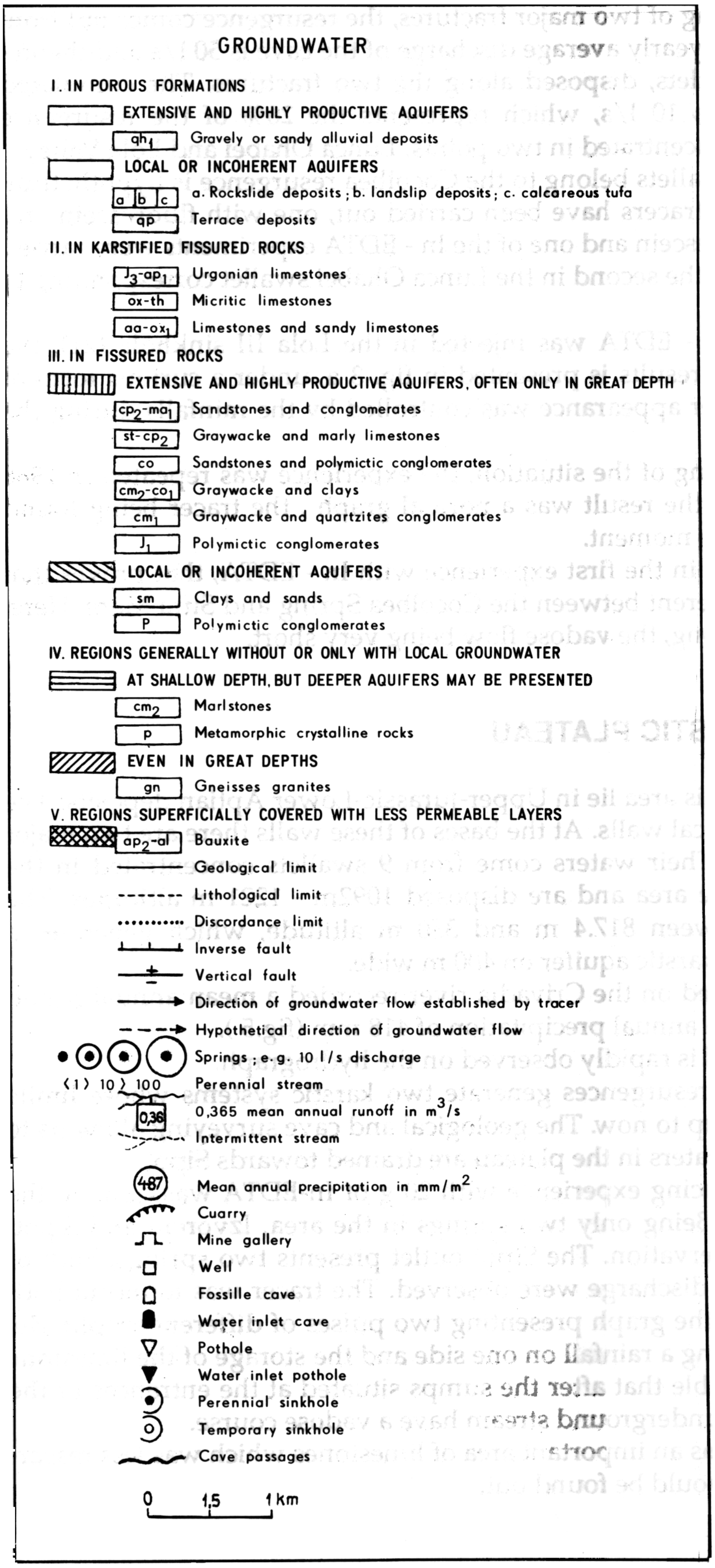


Fig. 2 - Numbers on the map figured near the springs or sinkhole sign



In June, 1988, 25 g of In-EDTA was injected in Lunca Ohabei Sinkhole to establish the hydrogeological boundary between the basin of Sura Mare and Cocolbea outlet.

The tracer appeared in both springs, in different rate, mainly in the Sura Mare cave. The rainfall from those days are reflected in the general form of the graph. The appearance of the tracer in the Cocolbea spring is determined by a main tectonic fault, and the lag between the two appearances is due to the fact that vadose flow did not exist, the storage of the Cocolbea spring being longer.

300 m downstream of the entrance of the Sura Mare cave, on the right side there are 3 karstic springs (9), disposed on a 15 m distance, having a cumulated discharge of 13 - 15 l/s. The average temperature of these springs is +16^{o} C, while the temperature of the water of the main river is between +5^{o} C and 14^{o} C. According to temperature data it seems to be a separated aquifer bearing subthermal waters.

THE COCOLBEA KARSTIC SYSTEM

The Cocolbea (Sura Mica)resurgence is the main outlet of the southern half of the Cioclovina - Ohaba Ponor karstic plateau. Situated at the crossing of two major fractures, the resurgence comes out from 125 m long cavity. The multi - yearly average discharge of the cave is 50 l/s and theoretically is supplied by 11 swallets, disposed along the two fractures. The cumulated discharge of these swallets is 10 l/s, which represents the 20% of the resurgence discharge. The swallets are concentrated in two points: Lunca Ohabei and Lola Valley.

The fact that all these swallets belong to the Cocolbea resurgence is hypothetical. Only three experiments with tracers have been carried out, one with fluorescein and two with In - EDTA. The fluorescein and one of the In - EDTA experiments were carried out in the Lola sinkhole while the second in the Lunca Ohabei swallet corresponding to the point named Scarisoara.

In July, 1987, 35 g of In - EDTA was injected in the Lola III sinkhole (21), the furthest from the spring. The results is presented in fig. 3 a, under a curious form of graph. We think that the tracer appearance was controlled by the rainfalls during the experience.

For a better understanding of the situation, the experience was repeated in 1988 with 1 kg of Fluorescein and the result was a normal graph , the tracer being found after 10 days from the injection moment.

The graph is flatter than in the first experience with In - EDTA, that proves that the storage conditions are different between the Cocolbea Spring and Sura Mare. Here, the cave is only about 130 m long, the vadose flow being very short.

THE BOJITA TECURI KARSTIC PLATEAU

The karstic aquifers in this area lie in Upper-Jurassic-Lower Aptian deposits. The plateau is surrounded by vertical walls. At the bases of these walls there are two major springs ,Sipot and Izvoreni. Their waters come from 9 swallets concentrated in the northern half of the limestone area and are disposed 1092m - 1221 m altitudes. The resurgences are situated between 817.4 m and 350 m altitude, which generates a possible development for the karstic aquifer on 400 m wide.

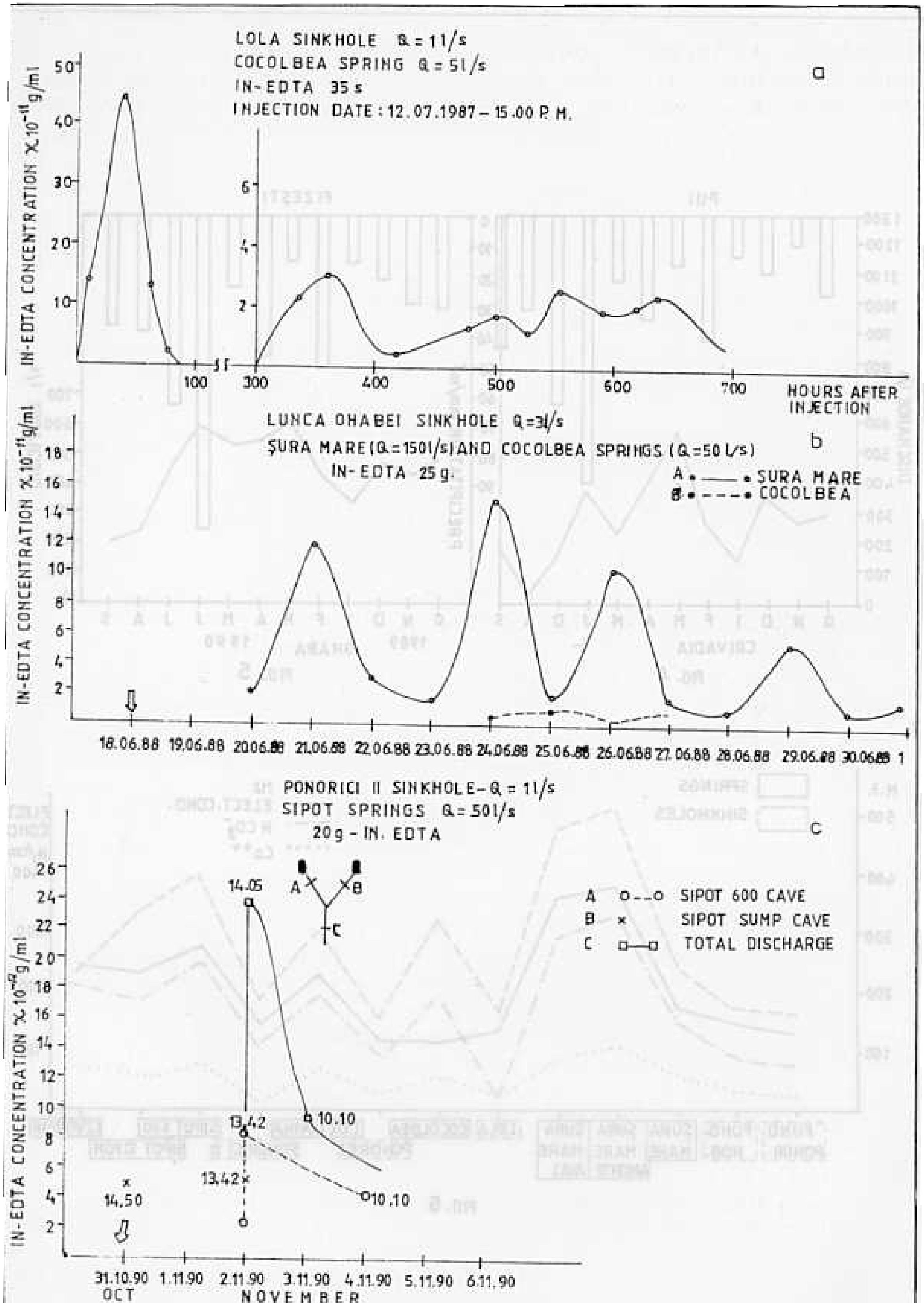
A gauging station situated on the Crivadia river recorded a mean annual runoff of 253 l/s, corresponding to an annual precipitation of 418 mm (fig.5).

The response of a rainfall is rapidly observed on the hydrograph.

The Sipot and Izvoreni resurgences generate two karstic systems whose limits remain only partially known up to now. The geological and cave surveying allow us to suppose that the majority of waters in the plateau are drained towards Sipot.

In November, 1990, a tracing experience with 20 g of In-EDTA was done in the Ponorici II sinkhole (fig.3c). Being only two springs in the area, Izvoreni and Sipot, both of them were under observation. The Sipot outlet presents two springs, both of them and also the cumulated discharge were observed. The tracer was found in both Sipot' springs after 48 hours, the graph presenting two pulses of different amplitude. The experience was done during a rainfall on one side and the storage of the limestone massif is reduced, being possible that after the sumps situated at the entrances of the Sipot caves springs, the main underground stream have a vadose course.

Izvoreni resurgence drains an important area of limestones which was less researched, where new water inlet would be found out.


LOLA SINKHOLE Q = 1 l/s
COCOLBEA SPRING Q = 5 l/s
IN-EDTA 35 g
INJECTION DATE: 12.07.1987 – 15.00 P.M.
a
IN-EDTA CONCENTRATION X 10^-11 g/ml
HOURS AFTER INJECTION
LUNCA OHABEI SINKHOLE Q = 3 l/s
ŞURA MARE (Q = 150 l/s) AND COCOLBEA SPRINGS (Q = 50 l/s)
IN-EDTA 25 g.
b
A SURA MARE
B COCOLBEA
18.06.88 19.06.88 20.06.88 21.06.88 22.06.88 23.06.88 24.06.88 25.06.88 26.06.88 27.06.88 28.06.88 29.06.88 30.06.88 1
PONORICI II SINKHOLE – Q = 1 l/s
SIPOT SPRINGS Q = 50 l/s
20 g – IN. EDTA
c
A SIPOT 600 CAVE
B SIPOT SUMP CAVE
C TOTAL DISCHARGE
14.05
13.42
10.10
14.50
31.10.90 1.11.90 2.11.90 3.11.90 4.11.90 5.11.90 6.11.90
OCT
NOVEMBER
Fig. 3

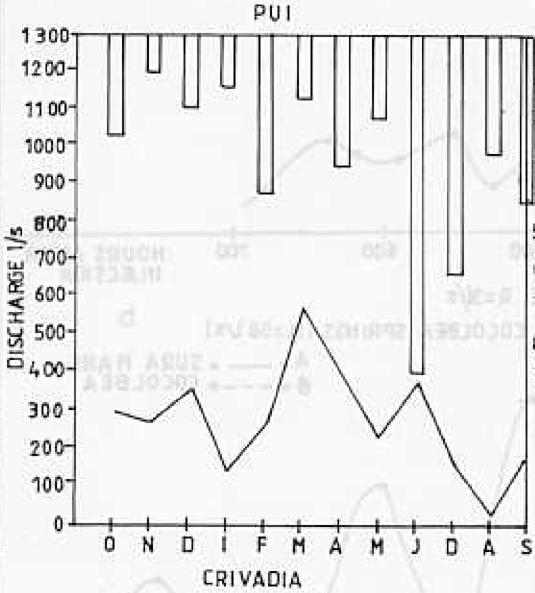


FIG. 4

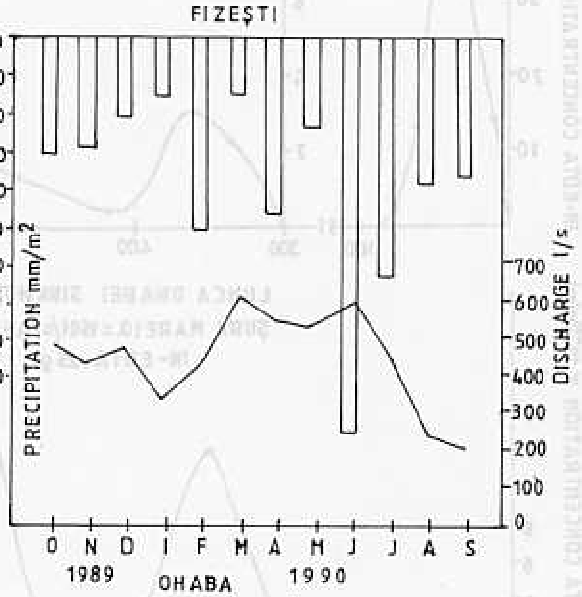


FIG. 5

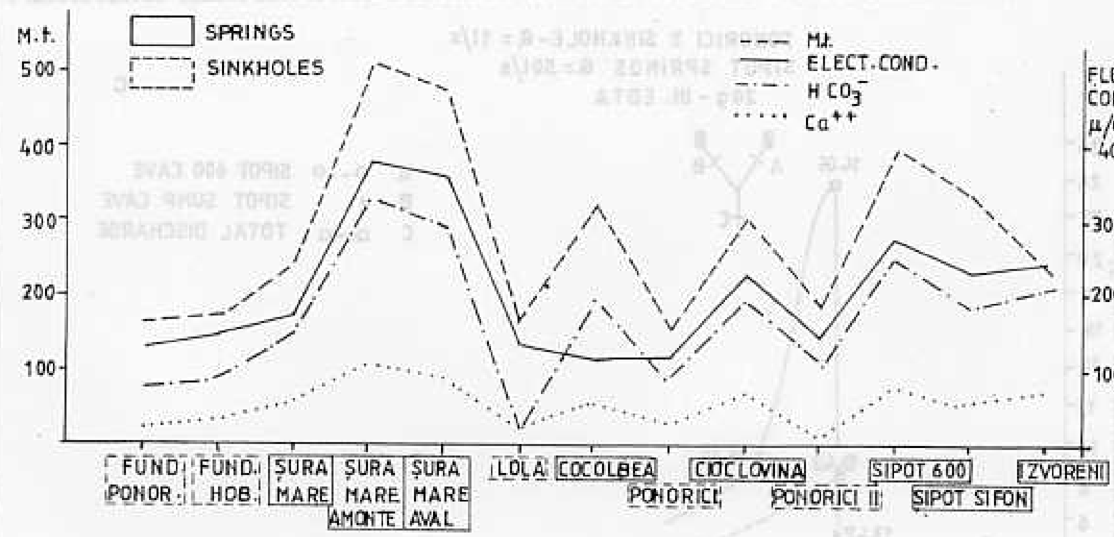


FIG. 6

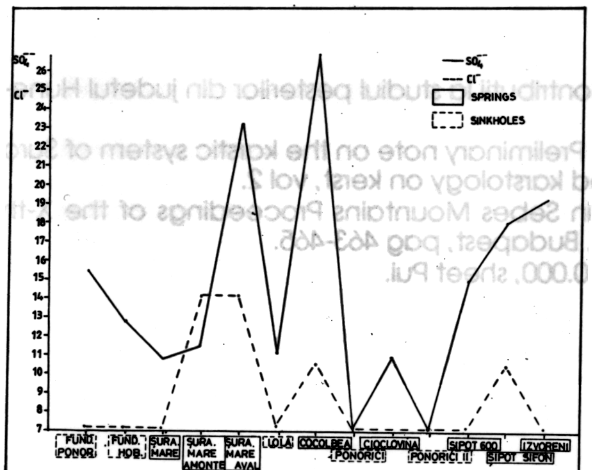


Fig 7

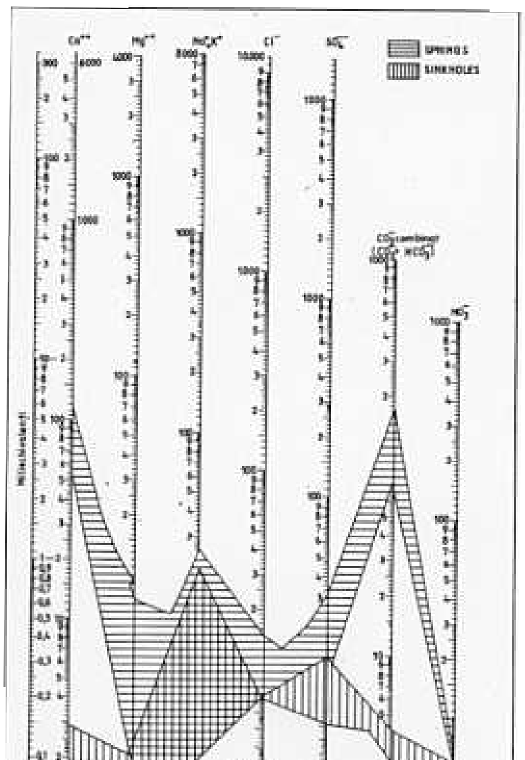


Fig. 8

Tecuri reservoir storage is about 60,000 cm/day.

From hydrochemical point of view, the matter samples collected in the area (about 50), both from river sinking waters and springs are characterized as waters with little mineralization.

In fig. 7 is presented the variation of SO_4^{--} and Cl^- in different springs and sinkholes. In general both cations are present in low rate, with three exceptions for the SO_4^{--} in Cocolbea springs and the two Sura Mare subthermal springs. The presence of SO_4^{--} demonstrate a longer storage of the water underground and a smaller influence of the rainfall waters.

Also the variation of the Ca^{++} and HCO_3^- correlated with the total mineralization and total conductivity are presented in Fig. 6. There are differences between the sinkhole and the springs. If the surface rivers present the maximun concentration of Na^+ and K^+ anions and SO_4^{--} cations, after crossing the limestone deposits, the characteristics of the waters change, increasing the value of Ca^{++} and HCO_3^- (Fig. 8)

NO_3^- cations are absent from all the samples, the water being unpolluted and apt to be used for water supply.

The Ponorici Cioclovina-Ohaba Ponor reservoir storage is about 35,000 cm/day, while Bojita

REFERENCES

DUMITRESCU, MARGARETA. ET AL. (1967 - Contributii la studiul pesterilor din judetul Hunedoara. Lucr. Inst. Speol. E.R. , tom VI.
HORIA MITROFAN, GEORGE PONTA (1985) - Preliminary note on the karstic system of Sura Mare (Sebes M.) Theoret. and applied karstology on kerst, vol 2.
GEORGE PONTA (1989) - Karstic Aquifers in Sebes Mountains Proceedings of the X-th International Congress of Speleology, Budapest, pag 463-465.
POP GRIGORE (1985) - Geological Map 1:50.000, sheet Pui.

Proceedings of the International Conference on Environmental Changes in Karst Areas - I.G.U.- U.I.S.- Italy 15-27 Sept. 1991 ; Quaderni del Dipartimento di Geografia n. 13, 1991 - Università di Padova, pp. 205-214

THE NULLARBOR CARBONATE AQUIFER, AUSTRALIA: THE IMPACT OF MAN AND SUGGESTIONS FOR FUTURE MANAGEMENT

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ABSTRACT

G.K.W.: resources, human impact, acquifers, water use and protection
Geogr. K. W.: Australia, South and West Australia, Nullarbor Plain

New data on the hydrogeochemistry of the Nullarbor carbonate aquifer indicate that the waters in the aquifer is of poorer quality and greater quantity than previously published assessments have proposed. Use and suggested future management of this water resource show that it can be maintained in its pure state.

INTRODUCTION

The Nullarbor carbonate aquifer lies beneath the Nullarbor Plain on the southern margin of the continent of Australia (Figure 1) and forms the major part (97.5%) of the Eucla Basin aquifer (Smith 1988). The Nullarbor Plain is the largest semi-arid/arid karst land in the world with an area in excess of 200,000 km^2. It is a vast unbroken low plateau of horizontal Eocene and Miocene limestones (Figure 2). The surface karst above the aquifer is poorly developed; vegetation is sparse and much of the plain is treeless. The major surface karst features are ridges and corridors with relief of 3-5 m amplitude and large but extremely shallow circular depressions called dongas (100-1500 m across, 2 - 3 m deep). A few hundred collapse dolines and tens of thousands of blowholes, both of which can lead to significant cave development, break the monotony of the karst surface.

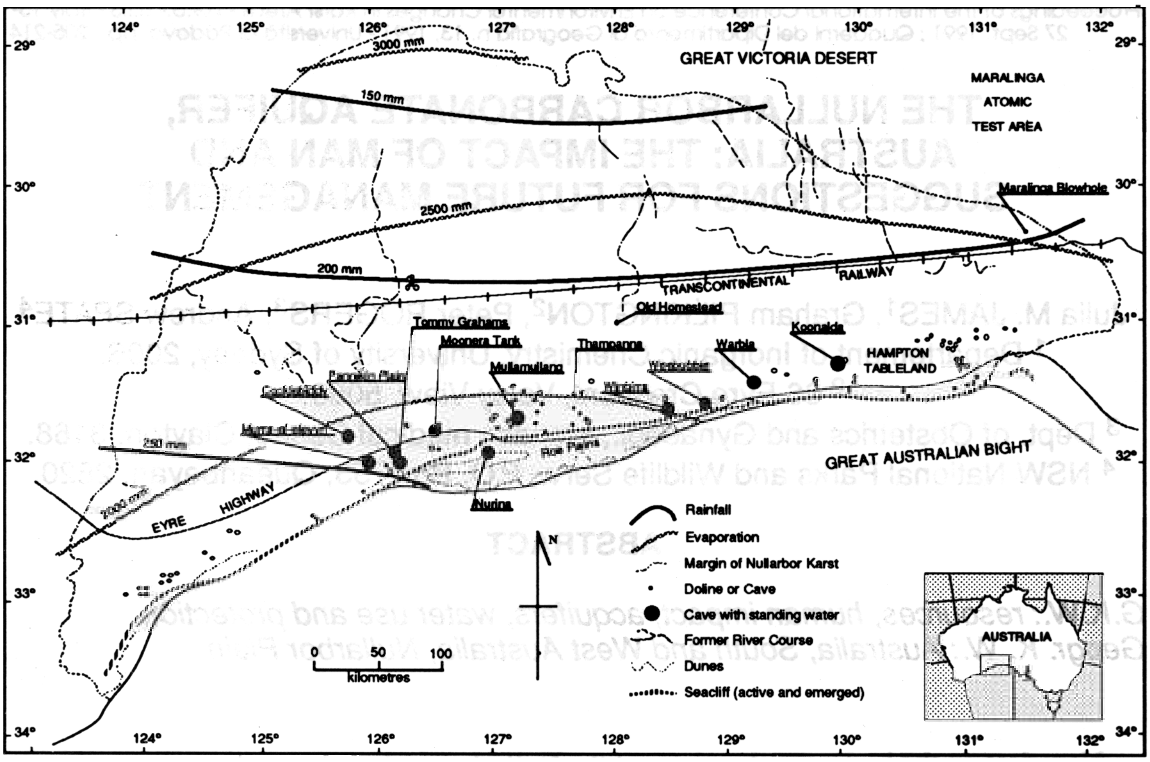

FIGURE 1 **THE NULLARBOR KARST** After Lowry and Jennings, 1974

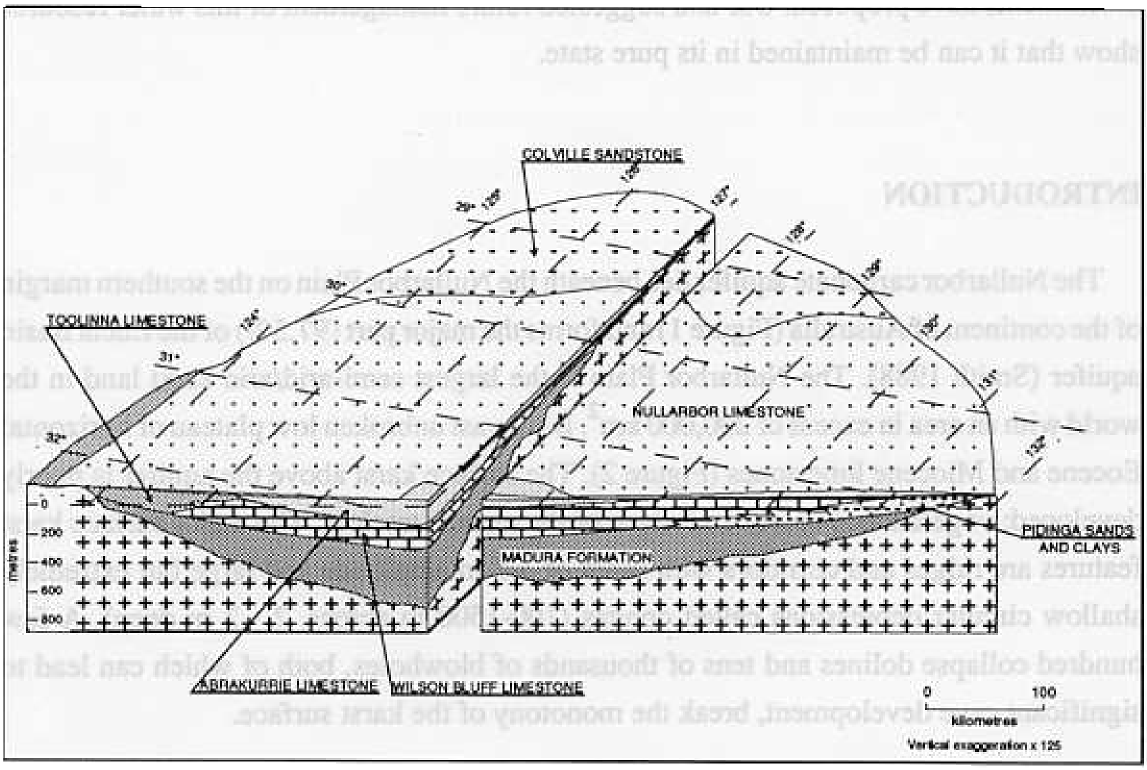

FIGURE 2 **EUCLA BASIN GEOLOGY** After Lowry and Jennings, 1974

Chemical studies (James *et al.*, 1989) and geomorphological observations by cavers, cave divers have been carried out in the water containing caves of the Nullarbor. The location of these caves is shown in Figure 1 and it should be noted that the most westerly and easterly sites are over 300 km apart and thus give excellent spatial representation of the quality of the waters in the Nullarbor aquifer.

Water chemical studies have led to the conclusion that the major erosive process currently active in the water filled passages of Nullarbor Caves is "mixing corrosion" taking place at the vadose - brackish water interface. The development of the air-filled caves is not well understood as cave passages and chambers have been considerably modified by gypsum and halite weathering by collapse. Despite this, there is considerable evidence that the caves are of shallow phreatic origin. This conclusion implies that in the past the aquifer has occupied higher levels in limestones. The surface of the Nullarbor aquifer is believed to be controlled by the sea-level and thus during the last glacial stage it would have been 60 - 100 m lower than at present. It should be added that perched water bodies occur due to clay deposited in cavities and because of the poor primary permeability. Hence phreatic-type solution and cave development can occur well above the normal standing water level.

To comment on the present state and future management of the largest carbonate aquifer in Australia is ambitious as the available data are limited. The following discussion is based largely on new data from the records of the Transcontinental Railway and sheep and cattle station owners. Thus conclusions and suggestions in this paper as to the nature and management of the aquifer are provisional.

THE NULLARBOR CARBONATE AQUIFER

Before a management plan for the Nullarbor carbonate aquifer can be attempted its present water quality and quantity must be established. It is equally important to understand how the aquifer is recharged so that it is not over used nor polluted.

Hydrogeology

The bulk of the aquifer lies in the Abrakurrie and Wilson Bluff Limestones (Figure 2), these limestones have high porosity and poor primary permeability (Lowry and Jennings 1974). The aquifer is encountered at variable depths: in the north water is found at relatively shallow depths of 30-45 m, on the Hampton Tableland at depths between 100 - 120 m and on Roe Plains at depths between 5-40 m. In the limestones above the aquifer small isolated pockets of better quality water have been found and in the non-karst rocks below the karst aquifer there is confined water.

The levels of water encountered in bores, wells and caves on the Nullarbor conform to a smooth surface declining southwards the direction in which the cave waters have been shown to be slowly moving. The gradient of the watertable is extremely low: as little as 20 mm km^{-1} in the Abrakurrie Limestone and 80-120 mm km^{-1} in the Wilson Bluff Limestone. Lowry and Jennings 1974 support the concept of a regional karst watertable below the Nullarbor. The aquifer is unconfined and unsaturated with the watertable marking the top of the phreatic zone. It has both conduit and diffuse flow characteristics; relative proportions of diffuse flow to conduit aquifer are not known but preliminary observations indicate that diffuse flow vastly exceeds conduit flow.

Water quality and quantity

Table 1 shows the water quality and quantity of the Eucla Basin carbonate aquifer as published in Smith 1988. The recent data indicate that this gives an excessively optimistic picture of the quality and a pessimistic view of the quantity of water available. Fresh groundwaters are extremely unlikely to be found and only small volumes of marginal groundwaters are obtainable from a limited number sources: from the bores on the north of the plain; from the creams ("freshs") which form on the cave lakes and from the coastal dunes and inland sand hills. Over 90% of the groundwater available is either brackish or saline. Brackish groundwaters are obtainable from most bores sunk on the Hampton Tableland and from Moonera Tank and Winbirra cave lakes. Borderline brackish/saline waters are found in Weebubbie Cave. Saline waters are found in the rest of the caves and from bores on the Roe Plains.

TABLE 1 QUALITY (% RESOURCE) AND DIVERTIBLE RESOURCES		
Fresh	< 500 mg L^{-1} TDS	9%
Marginal	500-1500 mg L^{-1} TDS	56%
Brackish	1500-15000 mg L^{-1} TDS	31%
Saline	> 15000 mg L^{-1} TDS	4%
Divertible resources 59 x 10^3 ML (million litres).		
Abstraction as percent of resource < 1%		Smith (1988)

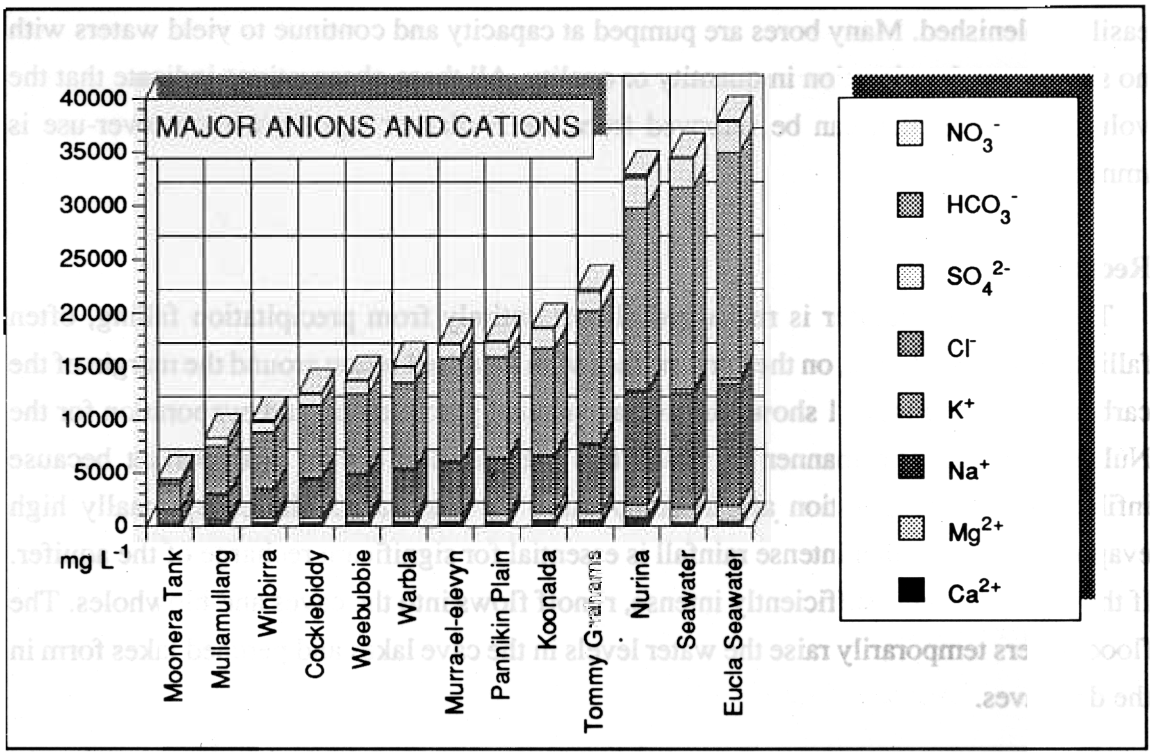

FIGURE 3 CHEMICAL ANALYSES FOR CAVE LAKES AND SEAWATER

The waters of the Nullarbor aquifer are dominated by sodium chloride and the salinity varies with source (Figure 3). Cave and bore waters are mostly saturated with respect to calcite. They are clean oxic waters and are not polluted (James *et al.*, 1991 in prep). Waters in the caves are at times stratified; after intense rainfall a lens of "fresh" water may be found on top of the brackish/saline lake waters and a saline/saline interface is found at approximately 20 m depth in some of the flooded cave passages. Bores are also recorded as having fresher water on top of brackish water; the deeper saline/saline interface has not been found.

The 59,000 ML in Smith 1988 for the divertible resource is a gross underestimate. Much of the surface is exposed Nullarbor limestone, a porous limestone of which the top 20 m is indurated. In spite of the induration, rain infiltrates with ease as there is much secondary porosity. For each millimetre of the annual precipitation that infiltrates to the aquifer some 200,000 ML of divertible resource is created, assuming no additional loss to the sea. The percentage of the annual precipitation that reaches the aquifer is unknown but it is expected to be several percent. The volume of water in the flooded cave passages is vast, for example Cocklebiddy Cave contains some 3,000 ML of water. It is an estimated that 2,000,000 ML of water flows south through the cave conduits each year (James *et al.*, 1989). Cave lakes that were pumped for water showed no noticeable change in level indicating the supply is easily replenished. Many bores are pumped at capacity and continue to yield waters with no significant deterioration in quantity or quality. All these observations indicate that the volume of water that can be removed from the Nullarbor aquifer without over-use is immense.

Recharge

The Nullarbor aquifer is recharged almost entirely from precipitation falling, often falling as intense storms, on the karst surface with localised runon around the margin of the carbonate rocks. Figure 1 shows the average annual precipitation and evaporation for the Nullarbor Plain. The manner in which this precipitation occurs is important because infiltration and evaporation are in competition for the water. The exceptionally high evaporation means that intense rainfall is essential for significant recharge of the aquifer. If the precipitation is sufficiently intense, runoff flows into the caves and blowholes. The flood waters temporarily raise the water levels in the cave lakes and perched lakes form in the dry caves.

The salinity of the water obtainable from the aquifer is an indicator of the degree to which the cyclic salts in the rainfall have been concentrated by evaporation and reflects how rapidly rainfall infiltrates to the aquifer. In the north of the Nullarbor there is much exposed limestone and the dongas have silty floors of windblown sand and precipitation infiltrates easily. In the south, clay filled depressions on the limestone surface collect runoff, infiltration is impeded, thus the cyclic salts in the precipitation are concentrated by evaporation and the seepage that does reach the aquifer is both limited and saline. Despite the higher average rainfall in the south the water in the aquifer is more saline than that in the north from lower but less regular and often intense rainfall. Other sites where there is believed to be fairly direct recharge of the aquifer are associated with structural features observable on air and landstat photos and interpreted by Lowry 1970 as faults of modest throw. The Hampton Range cliffs act as a runoff concentration area and lower salinity waters are found at their base. The rate of recharge of the aquifer is unknown and no tests have been recorded for bores that have become saline in order to review their status with time or if they will recharge with lower salinity water after heavy rain.

Uses Of The Nullarbor Aquifer

The pastoral industry is the major user of water from the aquifer. Sheep are able to drink the saline waters up to 14,000 mg L^{-1} TDS depending on age and sex and type of feed available (R. Egglington pers. comm.). The waters from the Nullarbor aquifer are too saline for irrigation and therefore the stock numbers at any time are controlled by the amount of feed available, which in turn depends on the rainfall. Semi-arid land management procedures are currently being employed on the Nullarbor and these ensure that the aquifer below the stations will retain its present quality.

Other uses of the water from the Nullarbor aquifer are for road making and for domestic use at the roadside and railway settlements. Much of this water, especially in the south of the plain, is drawn from saline bores and desalinated before use. As the tourist traffic across the Nullarbor increases there is expected to be heavier demand from these uses. Quarrying and drilling also take small quantities of water from the aquifer. The cave lakes are used for recreation, swimming in them is popular with tourists and local residents and the flooded conduits provide some of the best cave diving in the world.

Three caves, Weebubbie, Murra-el-elevyn and Koonalda, have been exploited for water. When these water sources were abandoned the pumping equipment and associated rubbish was left in the caves. Cavers have removed most of the rubbish from Murra-el-elevyn and Weebubbie. In Koonalda Cave, abandoned engines, platforms and pipeline complexes beside a number of the lakes still stand silent witness to variable quality and inadequacy of the supply. One of the lakes is polluted by sheep droppings washed in from the entrance and another lake with diesel oil and engine grease. Despite their poor appearance, analysis indicates that the lake waters are not chemically contaminated.

Future Management

Proving this resource by obtaining reliable data on its quantity and quality is of prime importance. Continued studies are needed to establish the relative proportion of conduit to diffuse flow. Recharge sites should be identified and rates of recharge should be established as soon as possible. Demand on this vast water supply is unlikely to significantly increase as potential for development on the Nullarbor is limited by climate and poor soils. At the present rate of abstraction over use of the aquifer is impossible, however, local over use may become more frequent when the better quality water is depleted. Such situations should be controlled by careful water use and by monitoring the water chemistry.

The major management task is to ensure that the aquifer does not become polluted during recharge. Known and possible recharge sites should be protected. The caves and blowholes are of prime importance. Management plans to protect the caves and karst will indirectly protect the Nullarbor aquifer, but a discussion of such plans is beyond the scope of this

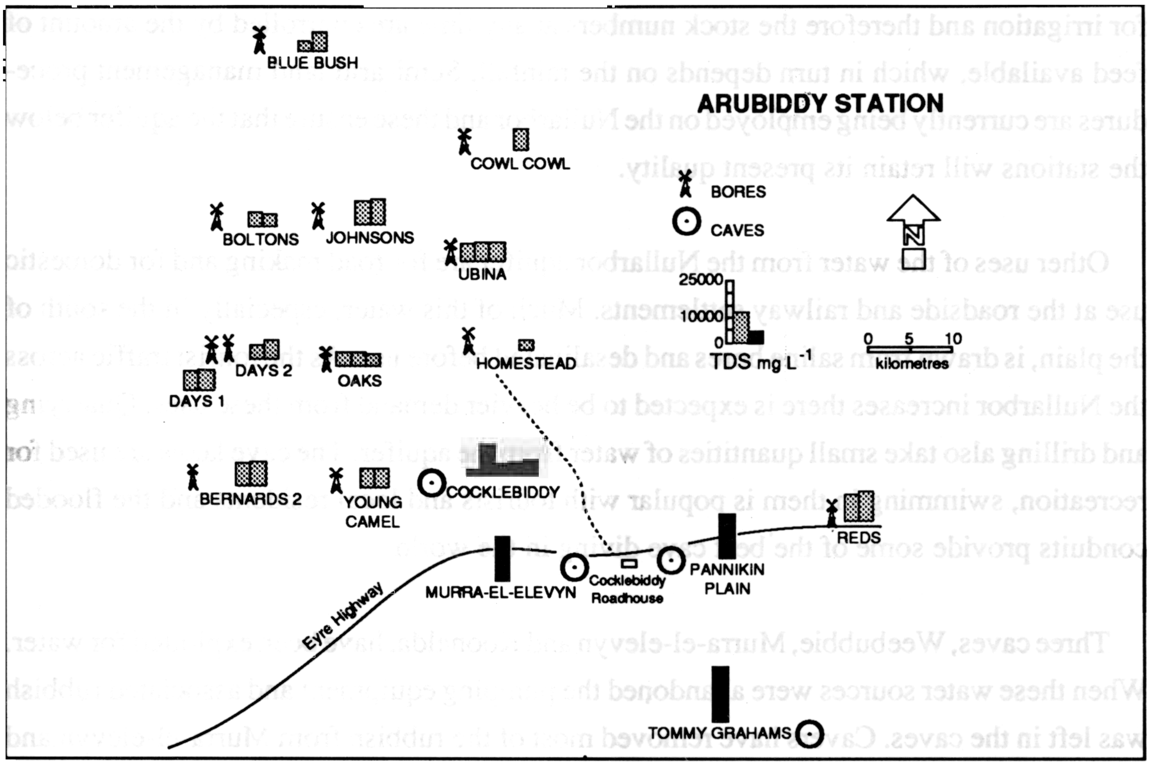

FIGURE 4 TDS FOR ARUBIDDY STATION AND NEARBY CAVES

paper. The recreational use of the aquifer should be allowed to continue as it is unlikely to significantly affect this robust system. However washing in the cave lakes using soap or detergents should be discouraged.

The myth that the cave conduits carry higher quality waters from north to south is indirectly discredited by this paper. Unless the cave lakes have a cream of "fresh" water they are of lesser quality than waters from nearby bores. Figure 4 illustrates this with water quality data for the bores on Arubiddy Station and for caves in the adjacent Nuyts Land Nature Reserve. In view of this it is unlikely that the caves will again be despoiled by the installation of pumps and pipelines.

Waste disposal sites should be chosen so that soluble and breakdown products of domestic and rural rubbish do not reach the aquifer. Rubbish should not be deposited in the shallow depressions, blowholes or caves. Waste disposal pits should be located in areas where there is a thick cover of clay on the karst surface. They should also be placed as far as possible from areas where the groundwater is good. Soluble waste such as the salts from desalination plants requires particularly careful disposal.

With major road and rail links across the Nullarbor it is possible a chemical or fuel spill could contaminate the aquifer. Diffuse vadose seepage and the porous nature of much of the aquifer means that any contamination is likely to be localised and dispersed slowly. The probability of such a spillage entering a main conduit and being transferred over vast distances is extremely low. It is not considered practicable to restrict the transport of such materials across the Nullarbor. The risk of radioactive groundwaters flowing south from the Maralinga atomic test site (Figure 1) contaminating the Nullarbor aquifer is also very low (James and Williams, 1986).

In areas of high evaporation enhancing artificial recharge to known aquifers is tempting as it allows the storage of flood flows from periods of intense rainfall. Any enhanced recharge of the aquifer could be extremely harmful to the caves and any fauna and flora that they support. Equally as bad is any action which prevents the natural recharge. Around the Murra-el-elevyn doline entrance is a bank of earth about 0.5 m high designed to stop vehicles approaching the overhung doline lip. This barrier has prevented runoff entering the doline and changed the micro- environment in both the doline and cave.

Quarrying is a potential impact that should be closely controlled above the aquifer because, although most of the pollution associated directly with limestone excavation can be contained, the removal of overburden and the creation of a pit will enhance local recharge of the aquifer and change its quality. However the quarrying of limestone is essential to the maintenance of both the road and rail links that cross the Nullarbor. Thus quarry sites should at least be located to avoid interference with major conduits, caves or drainage depressions.

Soil erosion will result in sedimentation of recharge routes and thus impede infiltration and increase the salinity of the aquifer but will not result in pollution unless sediments directly enter the cave lakes. Measures to prevent soil erosion through control of vehicle access, feral animals and fire will assist in maintaining the aquifer in its present condition.

CONCLUSION

The Nullarbor aquifer at present is pure and free from pollution. This vast water resource on the world's second driest continent has its own built in protection arising from its location beneath a desert and its salinity. Thus it only requires the minimum of management to retain its near pristine condition.

ACKNOWLEDGEMENTS

The authors wish to thank the many cavers and cave divers who have assisted in the collection of water samples and made geomorphic observations. The station owners and managers, in particular R. Egglington of Mundrabilla Station and P. Brown of Arubiddy Station deserve our special thanks for allowing access to their records and to the caves and other features on their properties. We gratefully acknowledge the permission granted by the National Parks and Wildlife Service of South Australia and Conservation and Land Management, West Australia to collect waters from caves under their jurisdiction.

REFERENCES

JAMES, J.M., ROGERS. P. and SPATE, A. P (1989) - Genesis of the caves of the Nullarbor Plain, Australia. Proceedings of the 10th International Congress of Speleology, Budapest pp 263-265.

JAMES, J.M and WILLIAMS, G.A. (1988) - Tietkens Plain Karst, Maralinga. Australian Radiation Laboratory Report No. ARL/TR081 pp 33.

LOWRY, D.C. and JENNINGS, J.N. (1974) - The Nullarbor Karst, Australia. Z. Geomorph. N.F. Vol 18, pp 35-81.

LOWRY, D.C. (1970) - Geology of the Western Australian part of the Eucla Basin Geol.Surv. W. A. 122.

SMITH, D.I. (1988) - Carbonate aquifers in Australia: a review. In Resource Management in Limestone Landscapes: International Perspectives, Eds D.S. Gillieson and D.I. Smith, Canberra pp 15-43.