Application of Tracers in Arid Zone Hydrology (Proceedings of the Vienna Symposium, August 1994). IAHS Publ. no. 232, 1995.

Salinity and isotopic dynamics of the groundwater resources on the Bolivian Altiplano

ANNE COUDRAIN-RIBSTEIN
URA CNRS, Circulations et Transferts Hydriques Continentaux, Laboratoire de Géologie Appliquée, Université Pierre et Marie Curie, 4 Place Jussieu, Tower 26, F-75252 Paris Cedex 05, France

PHILIPPE OLIVE
Centre de Recherches Géodynamiques, Université Pierre et Marie Curie, 4 Place Jussieu, F-75252 Paris Cedex 05, France

JORGE QUINTANILLA
Instituto de Investigación Química, Universidad Mayor de San Andrès, Bolivia

FRANCIS SONDAG
ORSTOM, Bondy, France

DAVID CAHUAYA
YUNTA, NGO, PO Box 14 529, La Paz, Bolivia

Abstract The aquifer under investigation is situated on the central Bolivian Altiplano and covers 1000 km^2. Perforated wells ranging in depth from 20 m to 80 m produce water whose electrical conductivity increases from upstream (0.5 mS cm^{-1}) to downstream (5 mS cm^{-1}). Hydrogeological modelling and interpretation of isotopic data (mainly ^{18}O with some ^{2}H, ^{3}H, ^{14}C and ^{13}C) has been conducted on data collected over two years from groundwater, rain, the Río Desaguadero and a core from the unsaturated zone. The aquifer presents two systems. The western low salinity zone is a consequence of infiltration from mountain runoff. Flow is northwards towards the Desaguadero and also southeastwards parallel to the mountains. The eastern zone of higher salinity results from a combination of recharge by the Desaguadero, groundwater evaporation and dissolution of salty sediments from ancient Quaternary lakes which dried up during a drier hydrological regime between 8000 and 1500 years BP.

INTRODUCTION

The Altiplano is a plateau 150 km wide by 1500 km long. It is situated between the Western and Eastern Cordilleras of the Andes which rise to altitudes in excess of 6500 m. Its own altitude ranges from 3810 m in the north (Lake Titicaca) to 3600 m in the south (salt flats). It is the most heavily populated region in Bolivia with the economy split between mining and agriculture. Within this endoreic hydrological system rainfall levels diminish from Lake Titicaca (600 mm) towards the Uyuni salt flat (150 mm). Conversely, the salinity of water resources increases as one travels from north to south.

The aquifer under investigation is sited in the central Altiplano and covers most of the province of Villarroel (Fig. 1) which is effectively isolated from the surrounding areas by the Río Desaguadero to the north and east and by the rugged hills of the Serranía Huayllamarca to the south and west. Around 10 000 traditional Aymaran people inhabit the province, living almost exclusively in scattered smallholdings. Since the severe drought of 1983, a Bolivian NGO (YUNTA) has been active within the province, drilling wells and installing hand pumps to replace the open, hand-dug wells previously used. Up to the present, nearly 100 wells have been completed and are the primary source of data for this study. They range in depth from 20 m to 80 m and tap water whose electrical conductivity increases from upstream values of 0.5 mS cm^{-1} to downstream values of 5 mS cm^{-1}. This study of an intermediary zone of the Altiplano with respect to water salinity and climatic parameters provides valuable information concerning the movement of groundwater and origin of its salinity. It is based on the application of hydrogeological modelling and isotopic techniques.

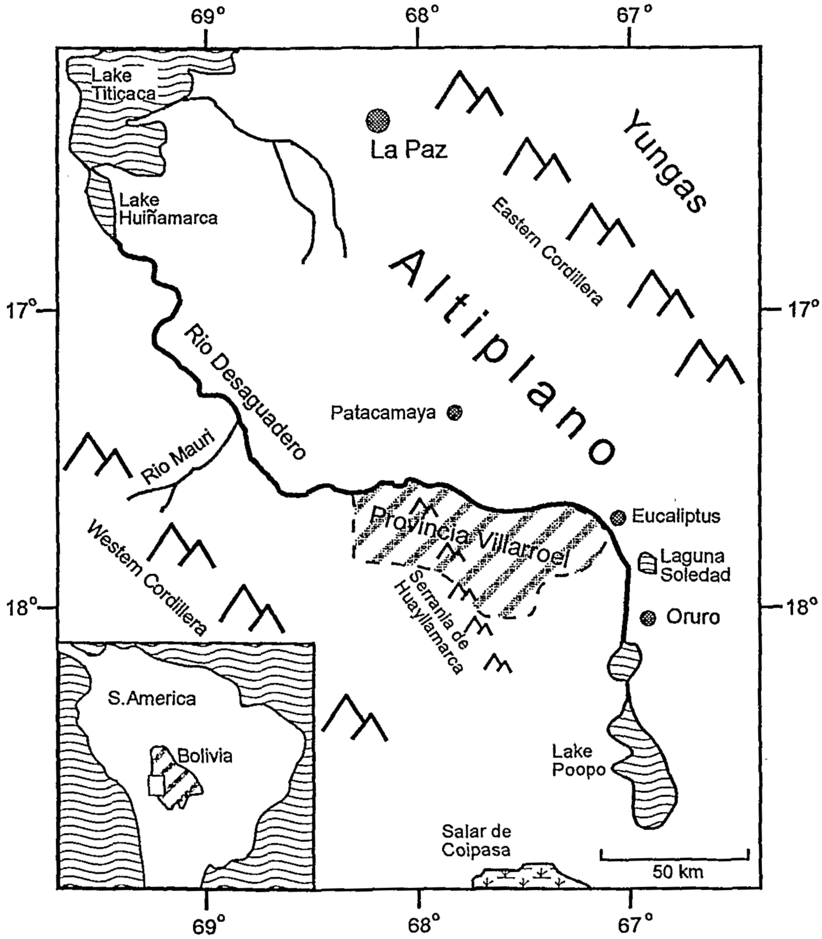

Fig. 1 Geographic situation of Bolivia, the Altiplano and Province Villarroel.

METHODS

Piezometric data were gathered during two major campaigns with ten reference wells being selected for closer scrutiny. A 20 m contour step is used on the 1:50 000 maps published by the Instituto Geográfico Militar. In order to obtain a higher precision of about 20 cm, surveying campaigns were carried out on 40 wells throughout the province.

The electrical conductivity of 110 water samples was measured during two major campaigns (October 1992 and April 1993) and more frequently on ten reference wells. It was measured in the field and subsequently verified by three laboratories. Water samples for ^{18}O analysis were collected at 3 different points along the river (9 analyses conducted), from 25 wells (75 analyses) during high and base flow, from 24 monthly rain samples and from 20 cm thick samples from a 6 m core taken from the unsaturated zone.

Five tritium analyses were conducted on 11 samples from the Desaguadero and from four wells. Five analyses of ^{13}C and ^{14}C were performed on groundwater samples obtained with the dissolved inorganic carbon (DIC) being precipitated out with barium chloride.

All the tritium, ^{14}C and ^{13}C and most of the ^{18}O analyses were conducted at the Centre de Recherches Géodynamiques at Thonon (France). The ^{2}H and some of the ^{18}O analyses were conducted in the Laboratoire d'Hydrologie et de Géochimie Isotopique at Orsay (France). The stable isotopes (^{18}O, ^{2}H) are expressed in ‰ units with respect to the international SMOW standard. The tritium analyses are reported in tritium units (TU). The ^{14}C activities are expressed in % of modern carbon (pMC). The analytical precision is greater than 0.2‰ for ^{18}O, 2‰ for ^{2}H, 1 TU for ^{3}H, 0.8 pMC for ^{14}C and 0.2‰ for ^{13}C.

HYDROGEOLOGY

In this section we present the geology of the region, the flow of the Río Desaguadero, the results of our hydrogeological study and the present and paleo-climate. The central Bolivian Altiplano is a complex Tertiary-Quaternary region of inter-mountain foreland basins bounded to the west by the stratovolcanoes of the Western Cordillera and to the east by the folded and thrusting Palaeozoic sequence of the Eastern Cordillera. In the area under study (Coudrain-Ribstein *et al.*, 1995), the western limit of the aquifer is the flank of a faulted Tertiary anticline rising to 4500 m. To the east of this faulted limit, Province Villarroel is hilly with Tertiary sandstone units. The eastern half of the province is remarkably flat, consisting of a series of largely lacustrine Quaternary sediments overlying Tertiary and Palaeozoic formations. The province is bounded to the east by the flank of a faulted Palaeozoic system.

Overall, the climate is semiarid, with a markedly wet summer (December to February) during which the high-reaching anticyclones over the subtropical Andes produce precipitation. From the nearest meteorological stations and the measurements taken over 2 years in the Province itself, the mean annual rainfall in the studied zone is estimated to be 350 mm. The three wettest months supply up to 80% of the annual rainfall. The annual potential evaporation is around 1.2 m in Patacamaya (Vacher *et al.*,

1989) and 1.7 m at 30 km east of Eucaliptus (Herbas & Hufty, 1992). The area is also subject to large diurnal variations of temperature (Δ25 °C) and strong winds (Greeley *et al.*, 1989).

The Río Desaguadero is the only permanent stream within the region. The average flow out of the Lake Titicaca to the Desaguadero (Gutierrez, 1991) was around 16 m^3 s^{-1} over the 1956-1983 period, and 110 m^3 s^{-1} over the 5 wettest next years. It should be noted that during the dry years around 1970 a reverse flow towards Lake Titicaca was observed, as was in all likelihood the case during the dry period around 1940. According to Guyot *et al.* (1990), in our zone the headwaters of the Desaguadero mainly originate from the Lake Titicaca although the Mauri river is a tributary.

Steady-state hydrogeological modelling (Coudrain *et al.*, 1995) was carried out in order to simulate correctly the measured piezometric heads. At this stage of knowledge, the piezometric levels are compatible with the hypothesis that the aquifer is continuous across the Province Villarroel, being confined to the west and semi-confined to the east. The results indicate two sources of recharge (Fig. 2). To the west there is infiltration of runoff from the Huayllamarca mounts whilst to the east recharge comes from the Desaguadero. Connections between the Desaguadero and groundwater, in the same zone, are also indicated by a stochastic study of the Desaguadero flows (Llamas *et al.*, 1994). Our modelling also indicates that a net annual evaporation of 15 and 40 mm must be introduced in the northeastern zone ($X > 110$ km, $Y > 50$ km in Fig. 2). The hydraulic gradient varies from 10^{-3} to 0.65 10^{-3} from upstream to downstream. The permeability used in the model is in the range 10^{-5}-10^{-4} m s^{-1}.

During the Quaternary, several lacustrine transgressions occurred (Servant & Fontes, 1978), the earliest of which was Lake Tauca occurring around 11 000 years BP during a deglaciation period (Seltzer, 1993). This lake reached at least 3720 m and partly covered our aquifer. Reconstruction of Lake Titicaca fluctuations over the last 7000 years (Mourguiart *et al.*, 1992), indicate that water levels reached their minima around 7500 years and maintained levels lower than the weir to the Río Desaguadero until 1500 years BP. From these results and peat (Gouze *et al.*, 1986) and geochemical (Risacher & Fritz, 1992) studies, we may infer that Lake Tauca waters may have been connected to the aquifer under study, and afterwards from 8000 to 1500 years BP, the rain infiltration and recharge by surface water were less than at present.

ELECTRICAL CONDUCTIVITY AND SALINITY

Present groundwater conductivity increases from western values of 0.5 mS cm^{-1} to eastern values of 5 mS cm^{-1}. On each well, the standard deviation is small (SD < 0.1 mS cm^{-1}), except for those submitted to the Desaguadero influence (SD ≈ 0.3 mS cm^{-1} for $Y > 55$ km in Fig. 2), and for those situated at the confluence of the two flow regimes (SD $\approx$ 0.8 mS cm^{-1} for $X > 130$ in Fig. 2). Rain from the infiltration zone has a conductivity of 0.03 mS cm^{-1}. Hence, even though some rain samples may have conductivity up to 0.17 mS cm^{-1} near gypsum outcrops and salt flats, high salinity of groundwater cannot originate from the rain.

The electrical conductivity of Lake Titicaca is around 1.4 mS cm^{-1} with a TDS around 1 $\pm$ 0.2 g l^{-1} (Fontes *et al.*, 1979; Iltis *et al.*, 1992). The average of our measurements on the Desaguadero is around 1.8 mS cm^{-1} with a range of 3.28-

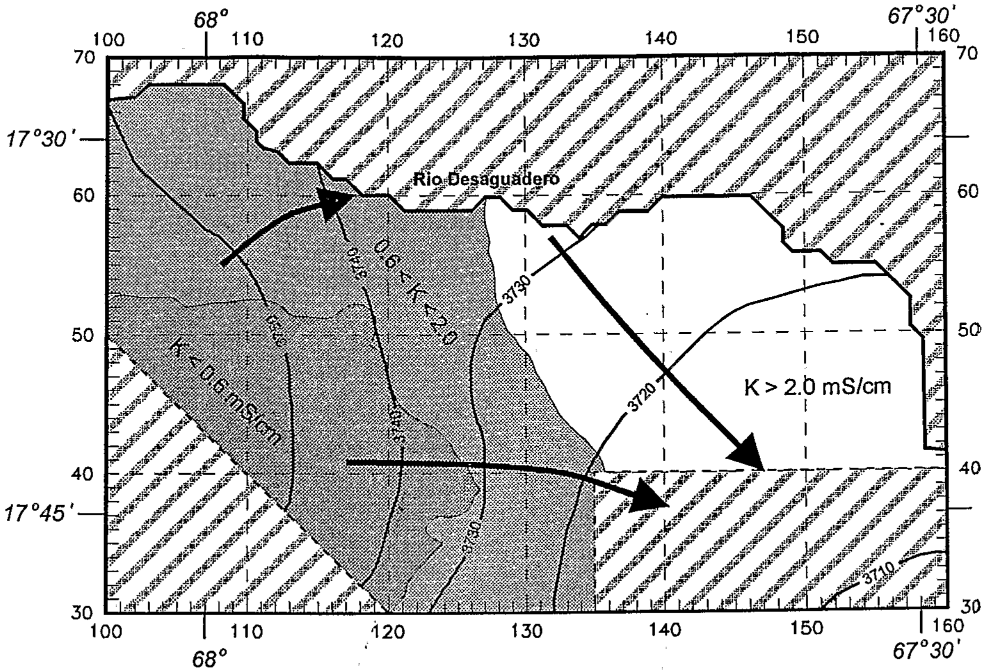

Fig. 2 Measured piezometric map, direction of flow and conductivity of the groundwater in the Province Villarroel. Axis coordinates are given in km (100 to 160 km in *X* axis) and degrees and minutes according to the maps published by the Instituto Geográfico Militar of Bolivia.

0.75 mS cm^{-1}. In the Soledad lagoon (Fig. 1), the salinity is 30 g l^{-1} (Mourguiart & Roux, 1990), and in the salar of Coipasa it is up to 300 g l^{-1} (Risacher & Fritz, 1991). Hence, the oft cited gradient from north to south does indeed exist, though the interannual variability is also important. At a same point on Lake Poopo, the salinity was 80 g l^{-1} in 1983 and 8 g l^{-1} in 1987 (Mourguiart & Roux, 1990).

Chemical analyses on leachates from the 6 m deep core in the unsaturated zone ($X = 146$, $Y = 41$ in Fig. 2) shows the profile of the present evaporation with chloride concentration increasing from 77 mg l^{-1} at 1.5 m depth to 800 mg l^{-1} near the surface. Similarly sulphate content increases from 50 mg l^{-1} at 1 m depth to 370 mg l^{-1} near the surface. Ancient evaporation is also indicated by a deeper high concentration of sulphate (420 mg l^{-1} at 1.5 m depth) and high chloride concentration (500 mg l^{-1} at 4.2 m). During the last dry period (7500-1500 BP), the paleo-salinity of Lake Huiñamarca reached 30 g l^{-1} (Mourguiart & Roux, 1990) and that of Lake Tauca was estimated at 60-90 g l^{-1} (Risacher & Fritz, 1991).

Therefore, downstream salinity in the east part comes partially from the recharge from the Desaguadero, and the high salinity of paleo-lake Tauca could have contributed to the present groundwater salinity by ancient infiltration and by present leaching of its salty sediments.

OXYGEN 18 AND DEUTERIUM

Groundwater measurements of $\delta^{18}O$ in Villarroel range between $-17.6‰$ and $-8.9‰$

and are distributed in three groups (Fig. 3). In the western part, values are less than −15‰; in the northeast zone, values are greater than −10‰; and in the southeast ($X > 135$; $Y < 48$), values are intermediary, between −14 and −10‰. It should be noted that one well, sited at a convergence point between the two flow patterns ($X = 146$, $Y = 41$ in Fig. 3), presents values varying between −10‰ and −15‰ while in the same time its electrical conductivity varies from 5.5 to 3 mS cm^{-1}.

Eight measurements of deuterium where conducted on groundwater. Six of them fall on the meteoric line ($\delta^2H = 8\ \delta^{18}O + 10$). The values from two wells from the salty zone ($X > 140$) deviate noticeably from this line with a slope of about 5. Values of $\delta^{18}O$ of the 6 m depth core decrease from 1.5‰ at the surface to −11‰ at 3 m depth. Below 3 m, the value is stable down to the saturated level. These features are congruent with the hypothesis of evaporation, but groundwater data from the saltier well deviates less from the meteoric line than the other one as would be expected. This indicates the existence of another source of salinization.

The excess in deuterium (defined by $d = \delta^2H - 8\ \delta^{18}O$) is between 6.22 and −14.36 for the eight wells. These small values ($d < 10$) could indicate that some

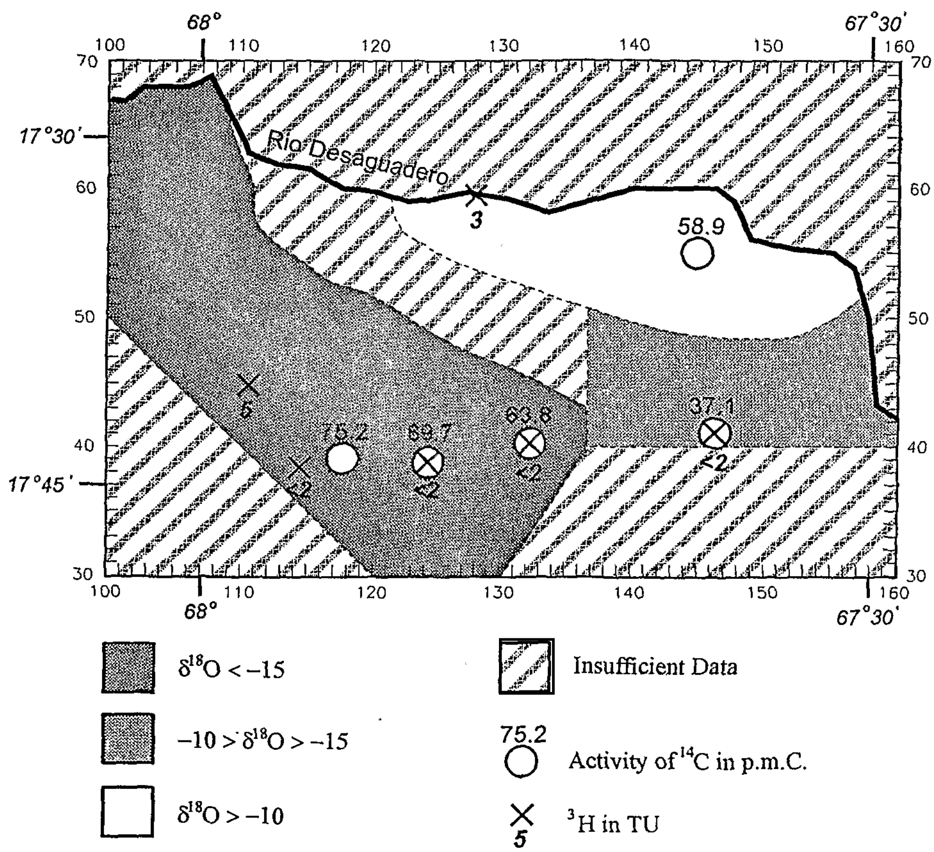

Fig. 3 Zonation of ^{18}O groundwater, values of ^3H and activity of ^{14}C in Province Villarroel. Axis coordinates are given in km (100 to 160 km in X axis) and degrees and minutes according to the maps published by the Instituto Geográfico Militar of Bolivia.

portion of the recharge occurred during a cooler climate as is proposed by Stimson *et al.* (1993) for the groundwater of the Bolivian Cochabamba valley with a 5 *d* value (200 km east and 1500 m below our area).

The rainfall samples collected for this study between November 1992 and March 1994 show a wide $\delta^{18}O$ range (−5 to −21‰). No altitude evolution of $\delta^{18}O$ is noted from the five pluviometers (3720-4220 m a.m.s.l.). However, $\delta^{18}O$ diminishes during the wet season and the rainfall likely to infiltrate has a mean $\delta^{18}O$ composition of −17‰. Aravena *et al.* (1989) state that the isotopic stratification observed in summer rains is not related to an altitude effect, but is instead linked to the location of the convective centres that generate rainstorms whose source is the Atlantic Ocean. These authors determined the following meteoric line for the Chilean Altiplano:

$$\delta^2H = 7.7\,\delta^{18}O + 9.7\ (‰) \tag{1}$$

The slope of this line (7.7), which is less than that of the world meteoric line (= 8), is confirmed by Alpers & Whittemore (1990) for the Chilean Atacama desert and by Stimson *et al.* (1993) in Cochabamba.

A study of 147 samples from Lake Titicaca collected in 1976 and 1977 from the surface down to 250 m, shows $\delta^{18}O$ values ranging between −4.42‰ and −3.76‰ (Fontes *et al.*, 1979). This publication indicates values of -50 ± 5‰ for the deuterium of the lake. A study by Lizarazu *et al.* (1987), on the region near the city of Oruro (Fig. 1), presents values for the Desaguadero of −5.27‰ $\delta^{18}O$ and −59.6‰ ^2H which reflect an evaporation pattern. In our study, the Desaguadero shows $\delta^{18}O$ values varying from −17.4‰ during a flood event to −6.4‰ during the dry season. For most of the year, out of the flood period, the mean value is −10‰. Hence, the Desaguadero appears impoverished in oxygen-18 in our zone in comparison with the upstream lake. This could be related to other contributions (Mauri river, groundwater?).

Guyot & Gumiel (1990) proposed explaining the salinity of wells on the western area of Oruro by infiltration of salty waters of inundation zone. Conversely, the isotopic study of groundwater undertaken near Oruro (Lizarazu *et al.*, 1987), and the present study show that no recharge is due to occur in the inundation zones.

Therefore, ^{18}O and ^2H data corroborate the two types of recharge, that is to say the infiltration of fresh water in the western piedmont and the Desaguadero recharge in the eastern zone, and the hypothesis of evaporation from downstream ground water.

TRITIUM

Four wells give a value lower than 2 TU and one well, near the recharge zone, gives 5 TU. The Río Desaguadero gives 3 TU. The IAEA network provides monthly precipitation ^3H concentrations, but the nearest stations are several hundred km outside our area. Aravena *et al.* (1989) analysed twelve precipitation samples in 1984 from several locations in the Chilean Cordillera. The average ^3H concentration was about 6 TU with a range of 9.9-3 TU. A tritium reconstruction in Cochabamba rainfall (Stimson, 1991) gives an estimation of 8 TU before 1952 and a peak of 70 TU around 1965. Two measurements on 1990 rain samples gave 8 TU. The author states that it is most probable that since the early 1980s the situation has returned to a steady-state with a value of 8 TU. However, it should be noted that according to IAEA (1992), the tritium concentration diminished in Bogota from a 1981 value of 6.1 TU to a 1987 value of 4.1 and in Ecuador from a 1981 value of 7.8 TU to a 1984 value of 4.9 TU.

The data published by Fontes *et al.* (1979) for Lake Titicaca show the average concentration of 31 samples taken in 1976 to be 8.0 $\pm$ 0.82 TU. More recently, Lizarazu *et al.* (1987) measured ^3H levels of 7.4 to 9.5 TU in rivers in the Oruro area. Therefore, the ^3H data indicate that the Villarroel groundwater is older than the 1950s except in the western recharge zone where it is few years old, and our measurements suggest that 3H concentrations have continued to diminish since the early 1980s.

CARBON 14

From the five measurements on the Villarroel groundwater, $\delta^{13}C$ varies between -11.7‰ and -7‰, and the activity of ^{14}C varies between 89.6 pMC and 37.1 pMC (Fig. 3). A discrepancy may be noted for the two western points. The increasing ^{14}C activity from 75.2 to 89.7 is not coherent with the flow pattern, but it may be explained by the high recharge inferred by the modelling around the point with the greater activity. These two points are likely to be influenced by recent activity up to 120 pMC as noted in the Oruro zone (Lizarazu *et al.*, 1987) and around 125 pMC for ^{14}C (1980-1981) in the Northern Chile, according to Aravena & Suzuki (1990).

For the three eastern points, assuming no recharge, the travel time may be estimated by the following equation (Mook, 1980):

$$\Delta T = 8270 \ln(a_{k+1}^{14}/a_k^{14}) \qquad (2)$$

where a_k^{14} is the ^{14}C activity of the k sample. This gives 3820 years from north to south (13.9 km) and 4480 years from west to east (14.1 km). These figures are equivalent to pore velocities of 3.6 and 3.1 m year^{-1} respectively. The pore velocity may also be approached by the following expression:

$$V_p = \frac{Ki}{\omega} \qquad (3)$$

where K is the permeability (L T^{-1}), i the hydraulic gradient and ω the porosity. Applying this formula, the estimated velocity is of the same order, between 2 and 5 m year^{-1}.

CONCLUSION

Two years worth of ^{18}O analyses for rain, the river Desaguadero and groundwater indicates that upstream in the western part of the region, groundwater has similar values (-15‰) to those of summer rainstorms which recharge the aquifer. In the zone where recharge by the Río Desaguadero is expected, the groundwater $\delta^{18}O$ values are greater (-10‰) and correspond to the mean low water value of the Desaguadero. Evaporation of downstream groundwater is inferred from present steady state hydrogeological modelling, analyses of a core in the unsaturated level of the downstream zone and data deviations in the $\delta^{18}O$-δ^2H graph. However, the relation between the electrical conductivity and $\delta^{18}O$ of groundwater shows that this evaporation is not sufficient to explain the increasing salinity. Dissolution of salty Quaternary sediments is likely to contribute to the excess salinity. Tritium and ^{14}C analyses indicate that the downstream groundwater is 4000 years old. Research on the Quaternary climate of the Altiplano indicates a drier climate between 8000 and 1500 years BP and that the Desaguadero was not supplied by the lake Titicaca. Hence, the salinity of the groundwater results from a combination of present recharge by the Desaguadero, evaporation from the groundwater and leaching of salty sediments of ancient Quaternary lakes and of a drier climate between 8000 and 1500 years BP.

Acknowledgements The authors thank Dr Zuppi of Orsay (France) for the ^2H measurements, Dr Vacher of ORSTOM in initiating the programme, Mr Martinez of the UMSA for his chemical analyses and Mrs Houpert of the Institute des Sciences de l'Ingénieur de Montpellier (France).

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Application of Tracers in Arid Zone Hydrology

Edited by

EILON M. ADAR
The Jacob Blaustein Institute for Desert Research, and Department of Geology, Ben Gurion University of the Negev, Sede Boker Campus, Sede Boker 84990, Israel

CHRISTIAN LEIBUNDGUT
Department of Hydrology, L. A. University, Werderring 4, D-79098 Freiburg, Germany

Proceedings of an international symposium held at Vienna, 22-26 August 1994. The symposium was organized by the International Committee on Tracers of the International Association of Hydrological Sciences and the Isotope Hydrology Section of the International Atomic Energy Agency, Vienna.

IAHS Publication No. 232
in the IAHS Series of Proceedings and Reports

Published by the International Association of Hydrological Sciences 1995

IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire OX10 8BB, UK.

IAHS Publication No. 232.

ISBN 0-947571-64-7

British Library Cataloguing-in-PublicationData.
A catalogue record for this book is available from the British Library.

IAHS is indebted to the Employers of the Editors for their invaluable support and services provided that enabled the Editors to work effectively and efficiently. In particular, IAHS would like to thank the Jacob Blaustein Institute for Desert Research, Ben Gurion University of the Negev, Sede Boker, Israel.

The following members of the Scientific Committee are warmly thanked for reviewing the papers:
E. M. Adar (Ben Gurion University, Sede Boker, Israel)
H. Hoetzl (Technical University Karlsruhe, Germany)
Ch. Leibundgut (L. A. University, Freiburg, Germany)
A. Schick (Hebrew University of Jerusalem, Israel)
B. Th. Verhagen (University of the Witwatersrand, Johannesburg, South Africa)
Y. Yurtsever (IAEA, Vienna, Austria)
The help provided by *D. E. Walling* (Exeter University, UK) who also helped review the papers is gratefully acknowledged.

The papers were checked and reformatted by Sarah Cage (freelance editor, Birmingham, UK) and Penny Kisby (IAHS Press, Wallingford, UK) using files provided by the first Editor. Sarah Cage corrected and assembled the final camera-ready pages.

Printed in Great Britain by Galliard (Printers) Ltd, Great Yarmouth.