

## **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 Andrés, 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<sup>2</sup>. Perforated wells ranging in depth from 20 m to 80 m produce water whose electrical conductivity increases from upstream (0.5 mS cm<sup>-1</sup>) to downstream (5 mS cm<sup>-1</sup>).

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  $0.5 \text{ mS cm}^{-1}$  to downstream values of  $5 \text{ mS cm}^{-1}$ . 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.

69°

68°

67°

## **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

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 ( $\Delta 25^\circ\text{C}$ ) 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  $16\text{ m}^3\text{ s}^{-1}$  over the 1956-1983 period, and  $110\text{ m}^3\text{ s}^{-1}$  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.

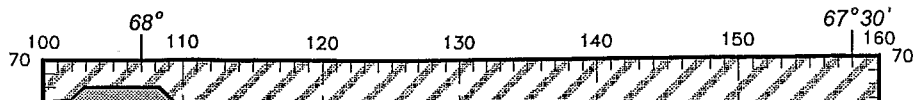
Steady-state hydrogeological modelling (Coudrain *et al.*, 1995) was carried out in order to simulate correctly the measured piezometric heads. At this stage of knowledge, the piezometric levels are compatible with the hypothesis that the aquifer is continuous across the Province Villarroel, being confined 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 ( $X > 110\text{ km}$ ,  $Y > 50\text{ km}$  in Fig. 2). The hydraulic gradient varies from  $10^{-3}$  to  $0.65 \cdot 10^{-3}$  from upstream to downstream. The permeability used in the model is in the range  $10^{-5}$ - $10^{-4}\text{ m s}^{-1}$ .

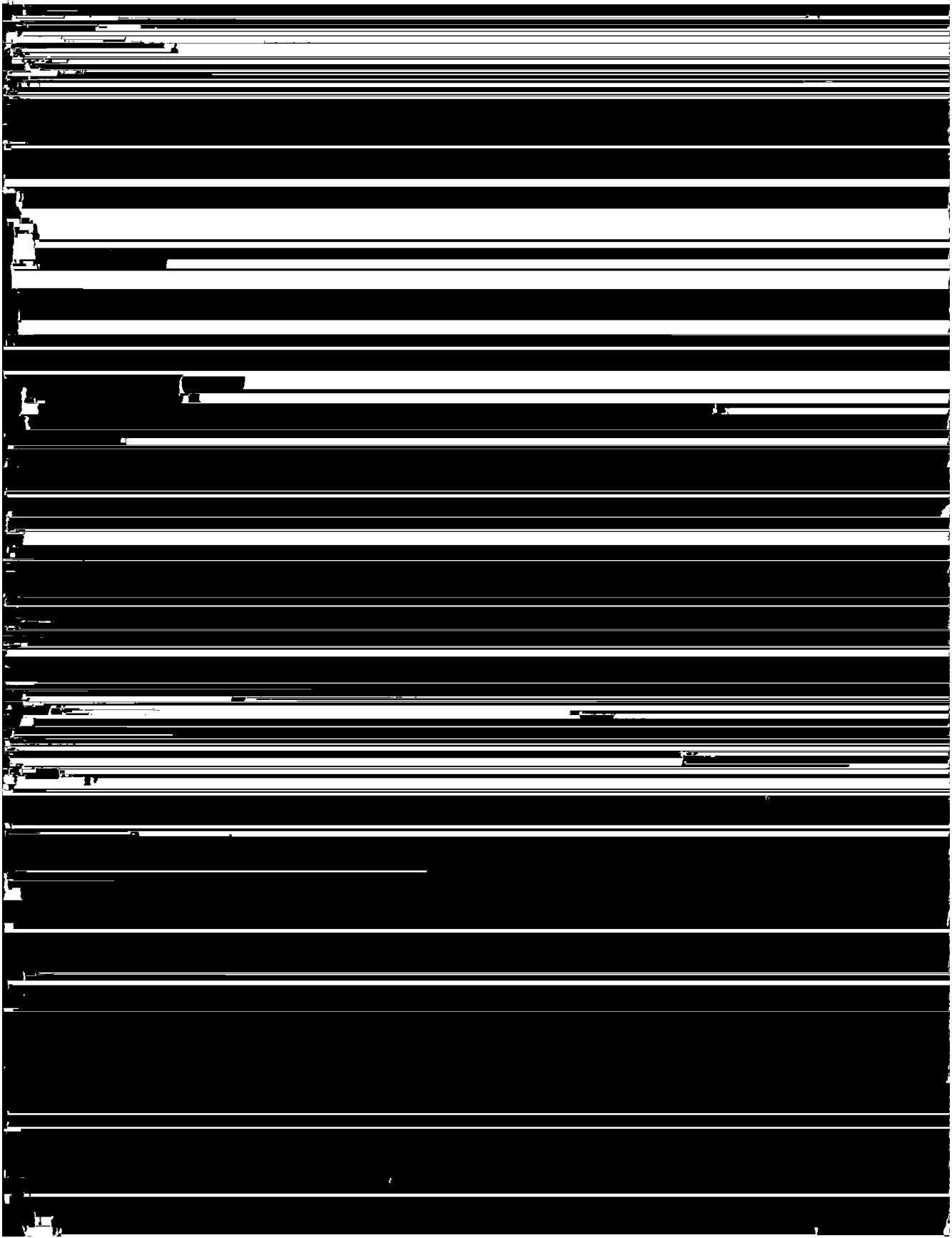
During the Quaternary, several lacustrine transgressions occurred (Servant & Fontes, 1978), the earliest of which was Lake Tauca occurring around 11 000 years BP during a deglaciation period (Seltzer, 1993). This lake reached at least 3720 m and partly covered our aquifer. Reconstruction of Lake Titicaca 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  $0.5\text{ mS cm}^{-1}$  to eastern values of  $5\text{ mS cm}^{-1}$ . On each well, the standard deviation is small ( $\text{SD} < 0.1\text{ mS cm}^{-1}$ ), except for those submitted to the Desaguadero influence ( $\text{SD} \approx 0.3\text{ mS cm}^{-1}$  for  $Y > 55\text{ km}$  in Fig. 2), and for those situated at the confluence of the two flow regimes ( $\text{SD} \approx 0.8\text{ mS cm}^{-1}$  for  $X > 130$  in Fig. 2). Rain from the infiltration zone has a conductivity of  $0.03\text{ mS cm}^{-1}$ . Hence, even though some rain samples may have conductivity up to  $0.17\text{ mS cm}^{-1}$  near gypsum outcrops and salt flats, high salinity of groundwater cannot originate from the rain.

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





portion of the recharge occurred during a cooler climate as is proposed by Stimson *et al.* (1992) for the groundwater of the Bolivian Altiplano with a 5% recharge

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



tivity and  $\delta^{18}\text{O}$  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  $^{14}\text{C}$  analyses indicate that the downstream groundwater is 4000 years old. Research on the Quaternary climate of the Altiplano indicates a drier

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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,*

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