Journal of Arid Environments (2003) **53**: 257–270
doi:10.1006/jare.2002.1034, available online at http://www.idealibrary.com on IDEAL®

Water resources in the semi-arid Pampa–Patagonia transitional region of Argentina

J. D. Paoloni*★, M. E. Sequeira†, C. E. Fiorentino★, N. M. Amiotti★, & R. J. Vazquez‡

★*Departamento de Agronomia, Universidad Nacional del Sur-CONICET, 8000 Bahía Blanca, Argentina*
†*CERZOS y Departamento de Ingeniería, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina*
‡*CIC y Departamento de Agronomía, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina*

The study was carried out in the zone corresponding to the Anzoátegui district (Province of La Pampa, Argentina), covering an area of 1600 km^2. This zone belongs to *the Caldenal* or *Southern Espinal*, an semi-arid region in central Argentina. The annual rainfall is 109/761 mm, but the annual evapotranspiration is as high as 1220 mm, so that the annual runoff is small compared with the annual rainfall. Since shallow ground-water is the principal source of water in the region, the hydrodynamics of the subterranean flow was evaluated and the depth variation of hydrostatic levels in relation to the surface was studied. Water quality was determined by hydrochemical analyses and classified for drinking water for cattle, human consumption and irrigation. It was found to be poor, 60·2% of the study area is affected by saline concentrations exceeds 5·0 dSm^{-1}. With respect to the ground-water-quality deterioration, reference was made to land use and management systems in the area, where the main economic activity is the cattle breeding, so that the vegetation has been degraded by overgrazing and deforestation for over 100 years.

Keywords: precipitation; hydrological balance, ground-water quality

Introduction

The extensive transition region between the Humid Pampa and Patagonia, where cattle breeding is the exclusive productive activity, is a semi-arid rangeland of central Argentina. An assessment and characterization of the water resources of the region provides information on (a) the spatial distribution and flow patterns of the water; (b) current and emerging problems with water quality; and (c) the background data required for promoting the socio-economic development of the region.

The aim of the present study is to evaluate the water resources in the south of the Caldén District (Boo, 1990), a phytogeographic region of 40,000 km^2 in central Argentina (Cabrera, 1976), commonly known as 'The Caldenal' (Pelaez *et al.*, 1997), with a view to ascertaining the quality of the water supply and obtaining the necessary

*Corresponding author.

0140-1963/03/020257 + 14 $35.00/0

data to assess the relative impact of cattle breeding in the region. This will form the basis for policy proposals for improving the management of local water resources, ultimately leading to higher sustainable productivity in the rangeland while preserving the renewable natural resources (Busso, 1997).

Ground-water in arid and semi-arid lands is considered to be a stable water not influenced directly by year-to-year climatic variation. This may be true if it is used to a renewable degree, but may not be true if the abstraction rate exceeds the natural recharge rate (Uitto & Schneider, 1997).

The water quality of ground-water is another issue to take into account. Generally speaking, the longer the ratio of the total water storage to the annual recharge rate (residence time), the higher the concentration of dissolved ions in ground-water. Therefore, the deeper groundwater is older and more saline than shallow ground-water (Uitto & Schneider, 1997).

However, very saline ground-water is sometimes found in shallow aquifers in arid and semi-arid lands. For example, the ground-water in the dry zone of Sri Lanka (Song & Kayane, 1996).

The following parameters were evaluated in order to obtain the required information on the water resources of the zone: precipitation regime; hydrological balance; piezometric configuration determined by means of an isohypse chart; and water quality, determined by chemical analysis and on the basis of isoconductivity and isobath data.

Study area

Site description

The study was carried out in the area corresponding to the 'Anzoátegui' topographic sheet of the Instituto Geográfico Militar (IGM) (Military Geographic Institute), scale 1:100,000, between 64° 30′ and 63° 30′W (the latter lying close to the border with Buenos Aires Province) and 38° 40′ and 39° 00′S, comprising a large part of the Department of Caleu Caleu in La Pampa Province, and covering a total area of 1,600 km^2 (Fig. 1). A main national road (route 22) run through the area from east to west, and a number of minor dirt roads connect cattle-breeding establishments with nearby towns.

Climate

The study area falls within a temperate semi-arid zone (Burgos & Vidal, 1951) with a mean annual precipitation of 384 mm for the period 1900–1988, according to data obtained from the locality of Río Colorado, close to the study site (Table 1).

Geomorphology

The area forms part of the transition region between the Humid Pampa and Patagonia landscape, with its characteristic semi-arid climate and stepped plains of decreasing elevation towards the modern age. There are two levels of plains, both with a slight regional gradient towards the east of usually less than 0·5%, separated by a narrow slope with a uniform projection of 20 m. The upper plain corresponds to the general level of the region's plains and is the older of the two, with an average elevation in the study sector of approximately 100 m a.s.l. The second plain is excavated into the first by the action of very ancient fluvial processes, most likely linked with interglacial action during the Pleistocene, and has an average elevation in the order of 80 m a.s.l.

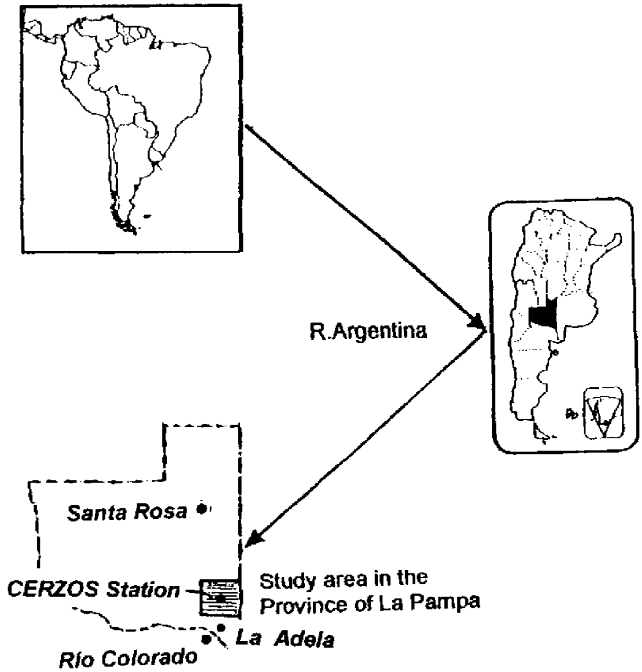

Figure 1. Study area.

Table 1. *Statistic of the Monthly and annual rainfall (mm), Rio Colorado*

Stat.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean	32·5	41·6	48·9	36·9	27·0	18·7	16·5	15·2	29·5	49·2	33·8	33·9	383
S.Dev.	32·4	41·3	45·9	42·2	28·5	23·7	19·9	18·6	30·8	44·9	33·2	30·4	135
CV	99·8	99·2	94·1	114	106	127	120	122	105	91·3	98·4	89·5	35·3
Max	156	187	259	167	168	119	103	80·6	131	253	152	134	761
Min	0	0	0	0	0	0	0	0	0	0	0	0	109
Range	156	187	259	167	168	119	103	80	131	253	152	134	652

The geomorphologic profile of the area shows a basal section with only the roof exposed and made up of thick compacted limolites, cemented on the upper portion by $CaCO_3$, giving rise to a petrocalcic paleosurface (sheet tosca).

A layer of eolian sediment was subsequently deposited in more than one pulse on top of this topography of the Pleistocene age, and it is the depth and texture of this layer that conditions the evolution of the soils in the area (Amiotti *et al.*, 2001). More detailed observation shows the significant presence of closed depressions, often salinized, which are larger on the first level of plain.

Soils

The soils in the area can be classified as Mollisolls, Entisols and Aridisols (Soil Survey Staff, 1999), each associated with particular features of the landscape.

On tablelands, soils develop on a shallow cover (generally <100 cm) of Holocene eolian sediment overlying a Pleistocene petrocalcic horizon (Paoloni & Gonzalez Uriarte, 1995). In these characteristically extensive, topographically flat, stabilized areas devoid of any microrelief, Calciustolls coexist alongside Paleustolls, both belonging to the Petrocalcic subgroup. Petrocalcic Calciustolls are predominant in the area and show A-C-2Ck-3Ckm horizon sequences. These shallow soils, showing weak melanization and calcium carbonate right from surface level and usually have a high concentration of secondary $CaCO_3$ at the base of the profile (2Ck), inherited from a previous pedogenetic cycle (Amiotti, *et al.*, 2001).

Very closely associated with these soils, though covering a smaller area, are the Petrocalcic Paleustolls with strongly developed mollic epipedons and calcic horizons underlying a totally leached solum. The evolution of these soils, with horizon sequences A-AC-Ck1-2Ck2 type, is closely related to the texture of the original material and exclusively associated with sediment containing a high amount of silt (loamy silt texture). In shallow depressions on the tablelands, soils with deep (30 cm or more), dark (10 YR3/1·5) surface horizons and strong to moderate structure occur. These soils lack petrocalcic horizon and leaching of CO_3Ca affects the whole profile. Moreover, have a silty loam and silty clay loam texture and classify as Typic Haplustolls. There is evidence of sedimentation in aqueous environments and of anaerobic iron reduction in the lower part of the profile. On slopes that connects terraces and deep depressions, pedogenesis is limited by landform instability. Soils profiles are deep, coarse-textured (sand and loamy sand) and weakly differentiated. They are classified as Typic Ustipsamments.

The predominant soils at the bottom of the deep, closed depressions are Typic Aquisalids and Aquic Ustorthents, with the distinctive salinization and hydromorphism features associated with their position in the landscape. The finely textured sediment characterizing the saline and alkaline soils at the bottom of the depressions derives from the selective transport of soil materials from high surroundings, and deposited in low water energy environments. In some places, these lacustrine sediments are superimposed by layers of coarse-textured material deriving from eolian sediments or colluvial deposits, thus increasing the vertical heterogeneity of the soil texture. The economic activities of the local population have had a detrimental effect on soil quality, and the surface horizons of soils where over grazing has occurred, have a marked structural deterioration compared with ungrazed soils (Villamil *et al.*, 2001).

Vegetation

The predominant vegetation is a deciduous woodland of *Prosopis caldenia* spatially distributed corresponding to three characteristic habitats. The first habitat comprises large solitary trees and low shrubs such as the 'caldén' (*Prosopis caldenia*), carob (*P. flexuosa*), 'alpataco' (*P. alpataco*), 'chañar' (*Geoffroea decorticans*), etc. (Cano & Movia, 1967). The second habitat is made up of a herbaceous stratum with species such as 'flechilla' (*Stipa tenuissima*), 'trébol de carretilla' (*Medicago minima)*, 'alfilerillo' (*Erodium cicutarium)*, etc. (Boo & Pelaez, 1991; Fresnillo *et al.*, 1991). The third habitat is characteristic of lake banks, the most frequent species being 'jume' (*Salicornia ambigua*), 'zampa crespa' (*Atriplex undulata*), and 'pasto salado' (*Distichlis scoparia)* (Cabrera, 1968).

Land use

The area is dedicated exclusively to cattle breeding, so that in many cases intensive or overgrazing, together with tree clearing in some areas, have accelerated the erosion process and eliminated a large part of the herbaceous cover.

Material and methods

Climatological information was obtained from the Servicio Meterologico Nacional (1990) for the locality of Río Colorado, which is the nearest town to the study area with sufficient historical records (1900–1988). In 1991, CERZOS installed an automatic meteorological station at a site called 'Mi refugio' (38° 46′S and 63° 40′W; elevation: 38 m a.s.l.). Although this station operates only intermittently, it was nevertheless possible to determine the relationship between rainfall intensity, duration and frequency (Sequeira, 1994). Precipitation was also recorded in the localities of Anzoátegui (1937–1980), Gaviotas (1921–1953) and La Adela (1956–1980).

Water samples were systematically obtained in the dry season from 120 wells and perforations and the depth of ground-water was determined. Chemical analyses were carried out in the laboratory, where the principal anions and cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}), toxic elements (As), conductivity and pH were determined. The sodium adsorption ratio (SAR) was also determined, and the water classified in accordance with the norms of the U.S. Salinity Laboratory (Richards, 1954).

The sampling sites were determined on the basis of information from the Military Geographic Institute (Anzoátegui sheet, scale 1 : 100,000) and isohypse, isoconductivity and water level maps.

The Penman–Monteith method (Smith, 1993) was used to determine potential evapo-transpiration (PET), based on the following: mean monthly relative sunshine (%); temperature (°C); relative humidity (%) and wind speed ($m\,s^{-1}$).

In order to calculate the water balance, real levels of evapo-transpiration were extrapolated from PET values according to the following equation:

$P = \mathrm{RET} + \mathrm{EX} + \mathrm{SWR}$, where P is the precipitation in mm RET = the real evapo-transpiration in mm, EX the excess water (runoff + infiltration) in mm, and SWR the soil water reserve for plant use in mm

where $\mathrm{RET} \leqslant \mathrm{PET}$, that is real evapo-transpiration is lower or equal to PET.

Results

Precipitation

The analysis of rainfall data is essential for determining the water balance in marginal zones like the study area. Figure 2 summarizes the monthly precipitation data for the period 1991–1995 in the Cerzos Station. Figures (3a–3d), show the relative annual frequency histograms for Anzoátegui, Gaviotas, La Adela and Rio Colorado, respectively. The slight differences are mainly due to the fact that the information refers to different intervals.

The most comprehensive meteorological information was obtained for Río Colorado by the National Meteorological Service (1990) and is assumed to be representative of the whole region. The monthly maximum, mean and minimum values of precipitation (Fig. 4) are presented for the period 1900–1988. Though the histogram of the relative frequency of annual precipitacion (Fig. 3(d)) shows a high degree of variability, there is an evident increase in annual rainfall from 1960 onwards as shown by fitting the series to a 9th degree polynomial equation (Fig. 5). The statistical results of the precipitation data for Río Colorado are summarized in Table 1.

A mean annual water balance was calculated for the 1900–1988 data series corresponding to Río Colorado, assuming precipitation to be uniformly distributed over the selected time interval (monthly) since no data are available for shorter periods.

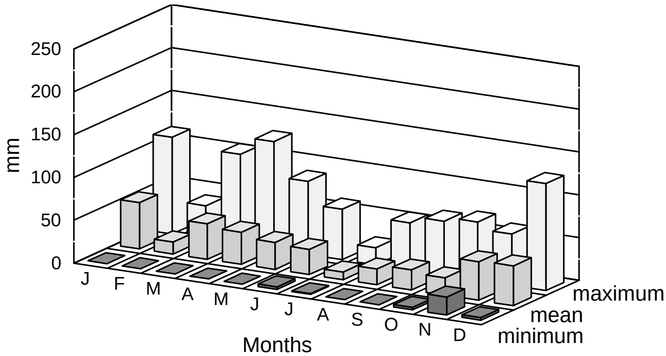

Figure 2. Cerzos station—Mean monthly precipitation (period 1991/1995).

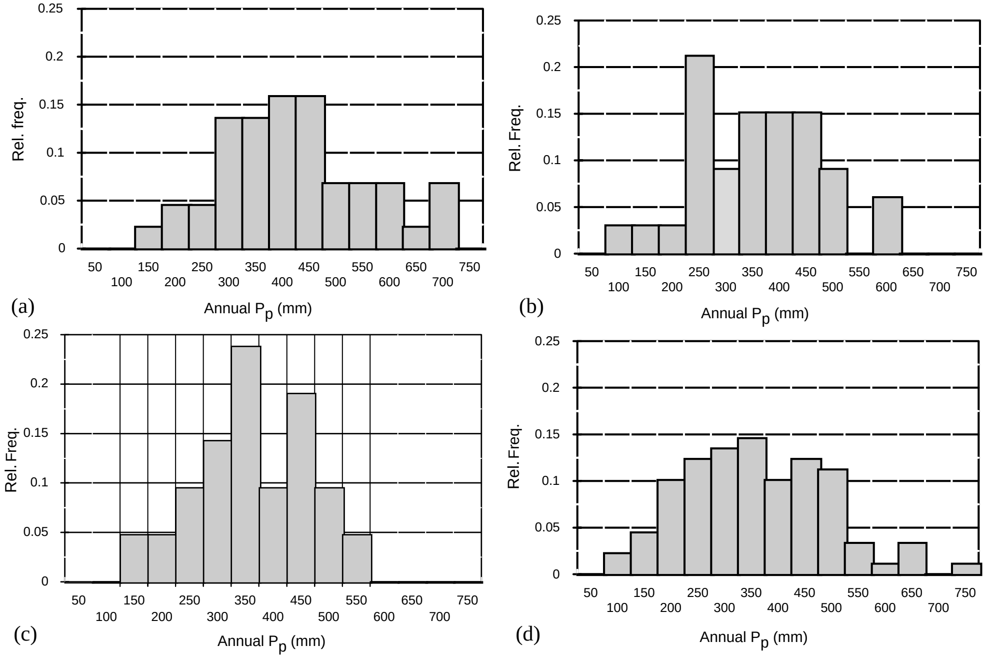

Figure 3. Histogram of annual precipitation, showing relative frequency): (a) Anzoategui station (period 1937/1980), (b) Gaviotas station (period 1921/1953), (c) La Adela station (period 1960/1980) and (d) Rio Colorado station (period 1900/1988).

As stated above, in order to calculate the water balance, real evapo-transpiration (RET) was extrapolated from PET values representing the upper limit of total water loss. Since the precipitation within any given month is non-uniform, the RET is probably somewhat lower than is indicated here, and the annual deficit somewhat less as well.

The results of the water balance analysis, assuming an initial water storage (SWR) of 100 mm in the predominant soils, are presented in Fig. 6. The annual deficit is shown to be 734 mm (Table 2).

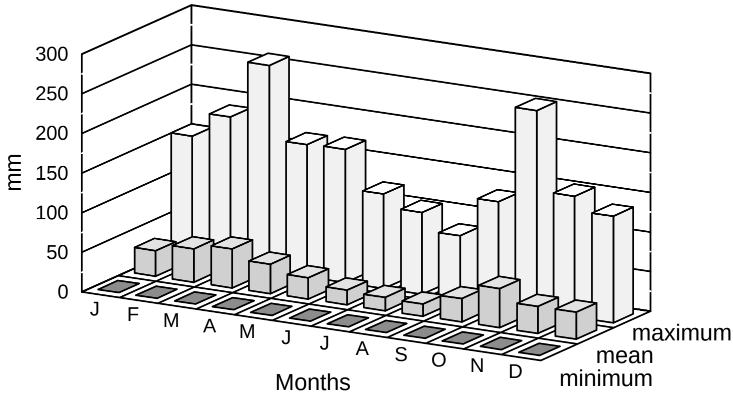

Figure 4. Rio Colorado station. Mean monthly precipitation (period 1900/1988).

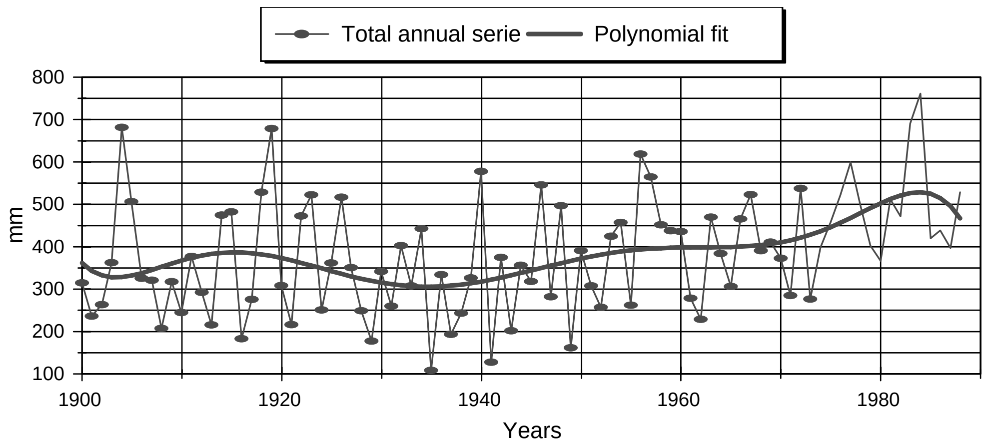

Figure 5. Rio Colorado station. Annual precipitation (period 1900/1988), with 9th degree polynomial fit.

Table 2. *Water balance for Río Colorado. Initial soil water reserve (SWR)=100mm. Values in mm*

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Tot.
P	15	29	49	34	34	33	42	49	37	27	19	17	385
PET	53	84	115	147	205	206	150	112	61	32	25	29	1219
Diff.	−38	−55	−66	−113	−171	−173	−108	−63	−24	−5	−6	−12	
SWR	62	7	0	0	0	0	0	0	0	0	0	0	
RET	53	84	57	34	34	33	42	49	37	27	19	17	486
Exc	0	0	0	0	0	0	0	0	0	0	0	0	0
Def	0	0	59	113	171	173	108	63	24	5	6	12	734

Note: Where *P* is the monthly precipitation (mm); *PET* is the potential monthly evapo-transpiration (mm); *Diff.* is the monthly difference between *P* and *PET*; *SWR* is the monthly soil water reserve (mm); *RET* is the real monthly evapo-transpiration (mm); *Exc* is the monthly water excess (mm); *Def* is the monthly water deficit (mm).

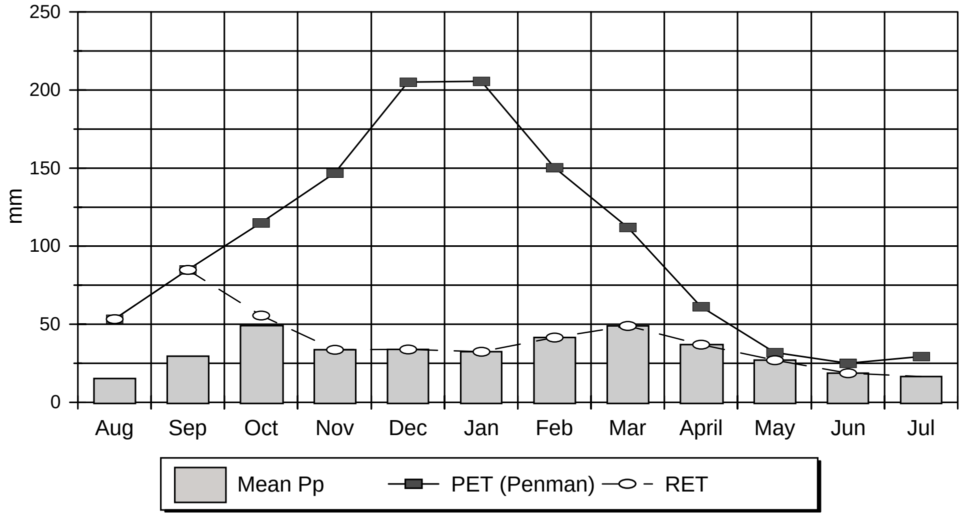

Figure 6. Rio Colorado station. Evapo-transpiration balance (period 1900/1988). PET: potential evapotranspiration; RET: Real evapotranspiration; Mean Pp: mean monthly precipitation.

Water resources

The only existing surface water is what drains from rainfall in the surrounding areas, showing a dendritic drainage pattern (INTA, 1980), and forming lagoons and salt pans in some of the depressions. These localized discharges are sometimes only temporary since the water is subject to direct evaporation as a result of the frequent winds.

Ground-water provides the only exploitable source of water, though the quality is poor. Phreatic water is present in the Río Negro formation, made up of grayish, fine-to medium-textured sandstone with intercalating clay and calcareous layers, whereas the exploited artesian aquifers are found in the sediment of the Chasicó geological formation (García, 1969).

The isohypse chart (water table elevation map) (Fig. 7), where the lines join the points of same hydrostatic head referred to as the topographic plane (m a.s.l.), shows hydrodynamic behavior of the ground-water flow, where an irregular and complex pattern of isopotential lines can be observed.

In the north-western quarter of the map, flows of a discharge zone can be seen flowing to the north-west, coinciding with a topographic depression that gives rise to the formation of a salt pan. The lines fall to values below zero and have a gradient of $7{\cdot}1 \times 10^{-3}$, measured from the divide at the 33 m a.s.l. contour. The lines fan out in a semicircular pattern from the bottom left angle of the chart, and the 23 m isopotential line extends diagonally through the center of the study area, demarcating a significant water divide with an average gradient of $1{\cdot}1 \times 10^{-3}$. This contour becomes undulating in the central part of the map, encircling three small, clearly defined areas with a north-easterly discharge, which then turns northward.

To the south, coinciding with and to the north of main road 22, are depressions with a lower hydrostatic head, which form discharge zones.

The isobath map (depth to water table) (Fig. 8) depicts a high degree of variability in the depth of water levels in relation to the land surface. Water table depth shows an inverse relationship with the topographic characteristics of the zone, with the greatest

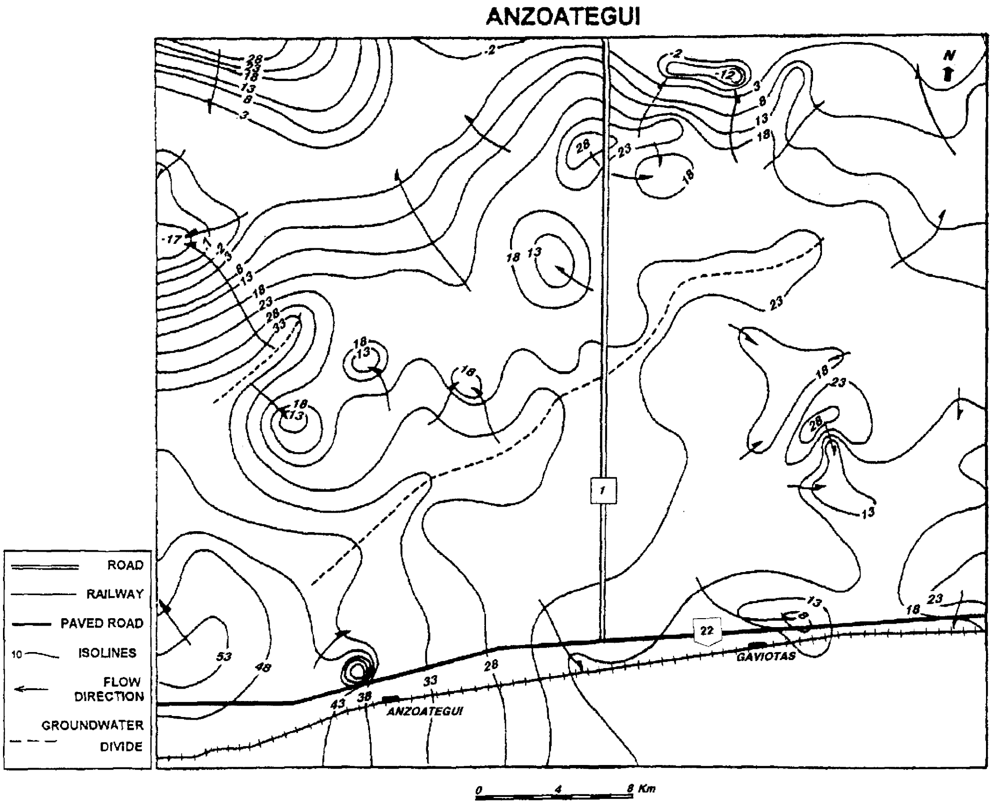

Figure 7. Isohypse chart (water table elevation) (m.a.s.l.) in the study area.

depths (70–80 m) corresponding to the highest elevations and the shallowest depths to depressions.

Water use

Most of the water from aquifers is brought to the surface using windmills, though in some places this method has been replaced by internal combustion engines owing to the need to ensure supply during periods with little or no wind or when greater extraction power is required to bring up water from depths greater than 80 m. Some wells in the study area, situated on the rim of salt pans or lagoons in depressions, have a natural surge. Approximately 95% of the water is accessed via perforations varying between 12 and 20 cm in diameter and between 6 and 100 m in depth. In a very few cases, open hand-dug wells can be found. The normal volume of water extracted ranges from around 1500 to 2800 $l\,h^{-1}$.

The water is used mainly for cattle, distributed from Australian-type tanks connected to drinking troughs. Use for human consumption is limited owing to the poor quality of the water, and the local population depends largely on the storage of rainwater.

Quality of the ground-water

Conductivity of the ground-water, which is a function of total soluble salts, was highly variable saline concentrations, ranging from 0·74 to 16·00 $dS\,m^{-1}$. The distribution of

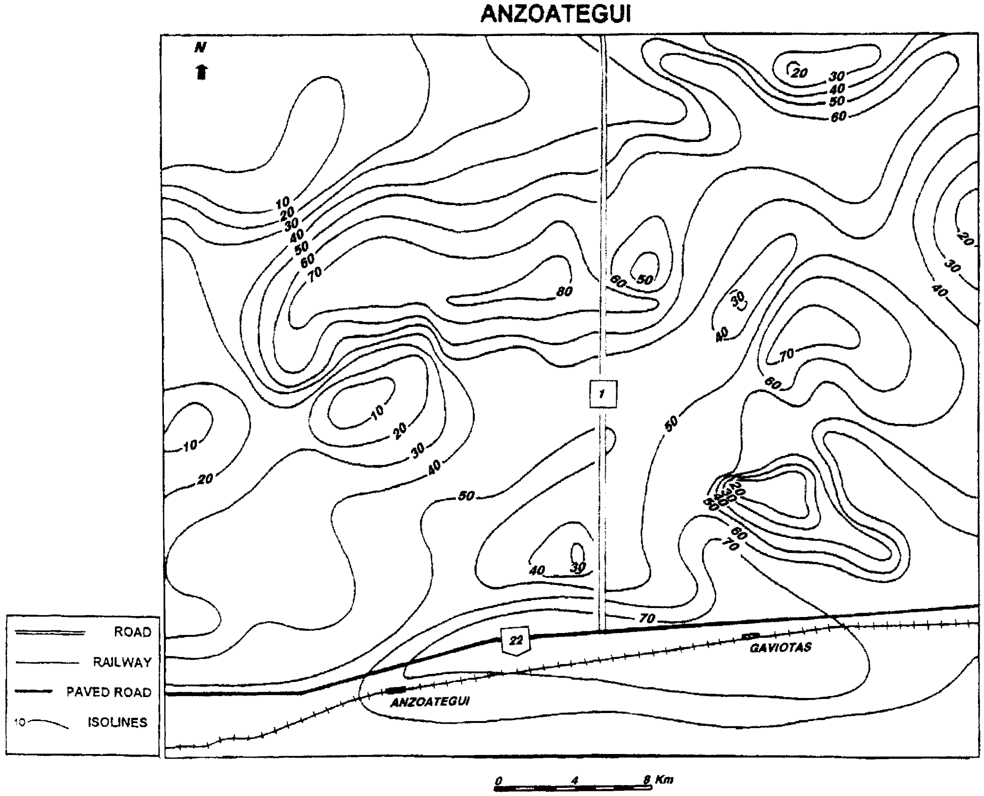

Figure 8. Isobath chart (depth to water table) (m) in the study area.

conductivities in the Anzoátegui area is shown in Fig. 9 (Fiorentino *et al.*, 1994). The irregular zones formed by the increase in the values of the contours indicate the discharge sites of underground aquifers, whereas areas of decreasing concentrations indicate sites of probable recharge. Four areas can be observed at the lower left and upper and lower center of Fig. 9 with values $<2{\cdot}00\,\mathrm{dSm^{-1}}$, indicating water of relatively good quality. Large, irregularly distributed high saline concentrations are brought into evidence throughout the area by a group of clearly defined zones with high contour values.

The high level of salinity in these latter areas is due principally to the presence of Cl^- and Na^+, which between them make up 77·7% of the composition of the water. On the basis of the results of the current analyses and taking into account the guide for the use of saline water for consumption by cattle (Ayers & Wescot, 1987), Table 3 shows the spatial and percentage distribution of salt concentrations. Water with up to $1{\cdot}5\,\mathrm{dS\,m^{-1}}$, of limited spatial distribution, is of excellent quality for animals, but characterizes only 2·8% of the region. From 1·5 to $5{\cdot}0\,\mathrm{dS\,m^{-1}}$, more widely distributed and occupying 37% of the study area, is considered of satisfactory quality, though its use is limited in the case of cattle not accustomed to drinking it. From 5·0 to $8{\cdot}0\,\mathrm{dS\,m^{-1}}$, occupying 51% of the area, is considered satisfactory by the guide (Ayers & Wescot, 1987), but should be used with caution since it produces physiological disorders in animals and is not recommended for use in cattle breeding. From 8·0 to $11{\cdot}0\,\mathrm{dS\,m^{-1}}$, the use of the water for cattle is limited, and as salinity

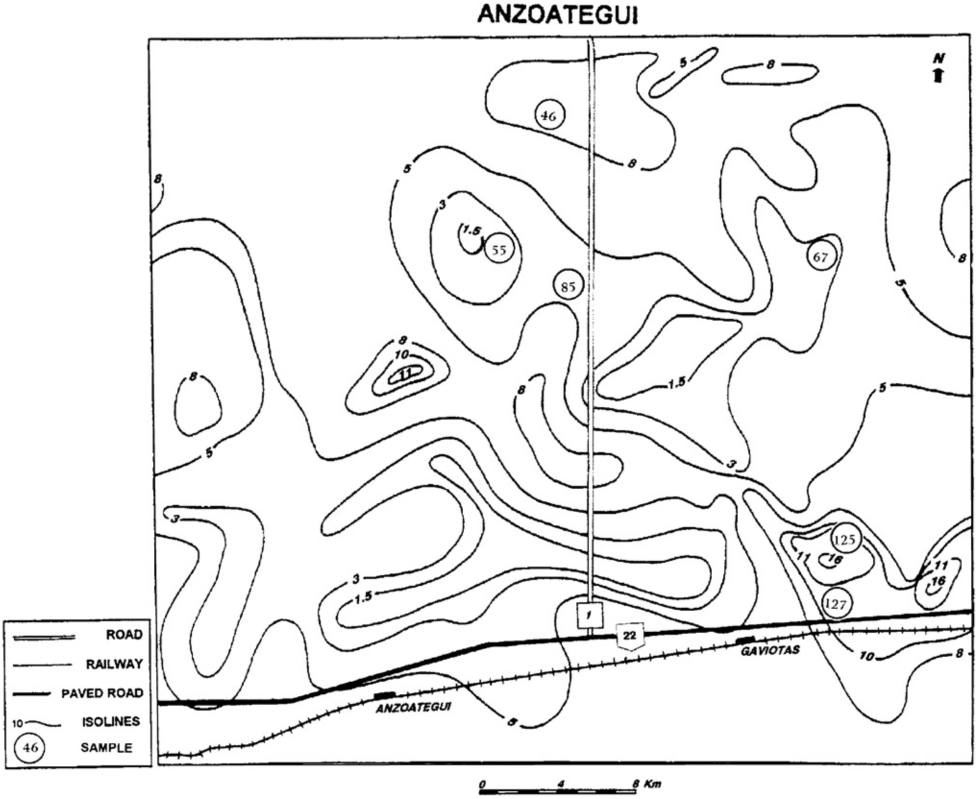

Figure 9. Isoconductivity chart (isolines of equal ground-water salinity)(dSm^{-1}) of the study area, showing total soluble salts expressed in terms of electric conductivity.

Table 3. *Spatial and percentage distribution of ground-water saline concentrations*

Conductivity range ($dS\ m^{-1}$)	Area (ha)	(%)
up–1·5	4600	2·8
1·5–5·0	57,900	37·0
5·0–8·0	82,300	51·0
8·0–11·0	13,500	8·3
11·0–16·0	1200	0·7
above 16·0	300	0·2

values increase, the water is classified as unsuitable. Finally, the use of water with $>5{\cdot}0\,dS\,m^{-1}$ can constitute an economic risk and affect the overall level of cattle production.

The use of the water for irrigation purposes in agriculture is limited since conductivity values above $1{\cdot}0\,dS\,m^{-1}$ are risky for many crops. Only 2·8% of the 161,000 ha analysed has water with an acceptable quality for irrigation (Fiorentino *et al.*, 1994).

Use of the water for human consumption is restricted under the regulations of the public health authorities. Measured in terms of conductivity, only 21·6% of the water is suitable for human consumption; in terms of sulfate content, only 25·8% falls within tolerable levels; and in terms of chloride content, 19·6% of the water is usable. From the point of view of arsenic content, 80·4% of the water is drinkable. The results shown refer to the total amount of samples analysed.

Taking into account the high variability of conductivity as observed in the isoconductivity chart (Fig. 9), six samples of increasing conductivity were selected and analysed from the point of view of chemical composition, risk classification on the basis of the sodium adsorption ratio (SAR) and saline concentration (Richards, 1954) (Table 4 and Fig. 9). Samples 55 and 67 present a mean level of salinity, whereas samples 85, 46, 127 and 125 show very high to excessively high levels, at which point the water is no longer recommended as drinking water for animals, for human consumption, or for irrigation.

The sulfate content in samples 55, 85 and 46, combined with high magnesium content, causes weight loss in animals as a result of alterations in the digestive process causing the elimination of mineral salts and also affects copper absorption, reducing the animals reserves of this element. High consumption of this water causes temporary diarrhea and lower forage ingestion, with the overall result that live-weight cattle yield is lower. Only sample 46 shows high levels of arsenic; cattle tolerance to arsenic varies between 0·15 and 0·30 $\mathrm{mg\,l^{-1}}$. The limit for human consumption is 0·05 $\mathrm{mg\,l^{-1}}$, and for irrigation purposes, levels no higher than 0·10 $\mathrm{mg\,l^{-1}}$ are recommended, although the tolerance level here varies from one crop to another (Ayers & Wescot, 1987).

Conclusions

The maximum mean precipitation in the study area occurs in autumn and spring and the minimum in winter, in accordance with regional characteristics. The analysis of the period 1911–1988 shows highly variable behavior, with a clear upward trend in precipitation since 1960. The annual rainfall is 109/761 mm, but the annual evapotranspiration is as high as 1220 mm, so that the annual runoff is small compared with the annual rainfall. Using the Penman–Monteith method, the hydrological balance shows an annual deficit of 737 mm, with maximum monthly values in summer. These results bring out clearly the marginal character of this area as regards agro-hydrological features.

Ground-water is the only potentially exploitable and accessible source of water for use in agriculture, cattle breeding, and for human consumption, though its use is limited because of high saline concentrations, 60·2% of the study area is affected by waters with $>5{\cdot}0\ \mathrm{dS\,m^{-1}}$.

These high salinity values are mainly the result of degradation of the vegetation by overgrazing. Once the natural forest had been cleared, the rate of soil evaporation during the dry season became very high. Then the soil water is easily evaporated, leaving dissolved salts near the soil surface. When the next rain comes, the infiltrated water dissolves the accumulated salts during the process of percolation to the water table. This resource is used only as drinking water for cattle, though even this has to be restricted in sectors where the saline concentration exceeds 5·0 $\mathrm{dS\,m.^{-1}}$

The authors are grateful to Magdalena Gonzalez Uriarte, for her assistance in the concepts about geomorphology and to Sergio Aman for his assistance in the field management portion of this study.

Table 4. *Composition of water samples and classification according to SAR and salinity*

Sample N1:	PH	EC (dS m^{-1})	Ca^{2+}+Mg^{2+} (meq l^{-1})	K^+ (meq l^{-1})	Na^+ (meq l^{-1})	Cl^- (meq l^{-1})	HCO_3^- (meq l^{-1})	SO_4 (meq l^{-1})	As (mgl^{-1})	SAR	Classif.
55	7·45	1·54	6·2	0·2	13·5	7·5	7·3	8·0	0·05	7·67	C_3S_2
67	7·95	2·92	10·0	0·4	27·5	12·4	14·5	4·7	Trace	10·0	C_4S_2
85	8·10	4·76	46·2	0·54	46·0	21·7	5·6	30·4	—	9·7	C_5S_2
46	7·0	8·07	41·5	1·2	52·0	47·3	3·3	54·0	0·5	11·4	C_6S_2
127	7·95	11·4	26·0	1·17	82·5	81·0	3·8	18·0	—	22·9	C_6S_4
125	8·45	17·1	30·5	1·25	122·5	132·5	2·8	15·0	0·05	31·4	C_6S_4

References

Amiotti, N., Blanco, M.C. & Sanchez, L.F. (2001). Complex pedogenesis related to differential aeolian sedimentation in microenvironments of the southern part of the semiarid region of Argentina. *Catena*, **43**: 137–156.

Ayers, R. & Wescot, D. (1987). Calidad del agua en la agricultura. *Riego y Drenaje*, pp. 1–173, Vol. **29**. Roma Food and Drink Administration (FAO).

Boo, R.M. (1990). Algunos aspectos a considerar en el empleo del fuego. *Revista Facultad de Agronomía-Universidad Nacional de La Pampa*, **5**: 63–80.

Boo, R. & Pelaez, D. (1991). Ordenamiento y clasificación de la vegetación en un área del sur del distrito del Caldén. *Boletin Sociedad Argentina de Botanica*, **27** **(3–4)**: 135–141.

Busso, C.A. (1997). Towards an increased and sustainable production in semi-arid rangelands of central Argentina: two decades of research. *Journal of Arid Enviroment*, **36:** 197–210.

Cabrera, A. (1968). Flora de la Provincia de Buenos Aires. Parte 1. *Colecc. Cientif. Del INTA,* pp. 1–653.

Cabrera, A. (1976). Regiones fitogeográficas argentinas: In: Kugler, W.F. (Ed.), *Enciclopedia Argentina de Agricultura y Jardinería*, Tomo 2, Fasc. 1, pp. 1–85. Buenos Aires. 1408 pp.

Cano, E. & Movia, C. (1967). Utilidad de la fotointerpretación en la cartografía de comunidades vegetales del bosque del caldén. *INTA, Serie Fitog*. **8**: 44.

Fiorentino, E.C., Paoloni, J.D. & Sequeira, M. (1994). Aspectos Hidroquímicos del Caldenal en la Hoja Anzoátegui. Usos y Restricciones. *XV Congreso Nacional del Agua*. La Plata, Argentina.

Fresnillo, D., Fedorenko, J., Fernandez, O. & Busso, C. (1991). Forage production of the annual legume Medicago mínima in semiarid rangelands of central Argentina. *IV International Rangeland Congress*, Montpellier, France.

Garcia, J. (1969). El agua subterránea en la cuenca de Bahía Blanca. Relatorio. *Reunión sobre la geología del Agua Subterránea de la Pcia. de Buenos Aires*. pp. 79–90. CIC, La Plata.

INTA (1980). Inventario integrado de los recursos naturales de la Pcia. de La Pampa. Buenos Aires, 40 pp.

Paoloni, J.D. & Gonzalez Uriarte, M. (1995). Geomorphological and edaphic aspects of the Pampas-Patagonian *Transitional Landscape for Water Resource Management. Arid Soil Research and Rehabilitation*, **9**: 235–243.

Pelaez, D.V., Bóo, R.M., Elia, O.R. & Mayor. M.D. (1997). Effect of fire intensity on bud viability of three grass species native to central semi-arid Argentina. *Journal of Arid Environments* **37**: 309–317.

Richards, L.A. (1954). Diagnosis and improvement of saline and alkali soils. *USDA Agricutural Handbook*, **60**: 1–160.

Sequeira, M. (1994). Régimen de las lluvias en el Caldenal—Análisis de intensidad-duración-frecuencia. *CERZOS*. Inédito.

Servicio Meteorológico Nacional (1990). Estadística Climatológica. Buenos Aires.

Soil Survey Staff (1999). Soil taxonomy. *Agriculture Handbook*, vol. 436 (2nd Edn). 869 pp.

Smith, M. (1993). *CROPWAT, Programa de ordenador para planificar y manejar riego*. Estudio FAO: Riego y Drenaje, Vol. 46. 133 pp.

Song, X. & Kayane, I. (1996). Zonal characteristics of groundwater quality controlled by climate in Sri Lanka. *Journal of the Japanese Association of Hydrological Sciences*, **26**: 151–165.

Uitto, J.I. & Schneider, J. (1997). *Freshwater Resources in Arid Lands*. ONU Global Environmental Forum V. United Nations University Press: USA.

Villamil, M.B., Amiotti, N. & Peinemann, N. (2001). Soil degradation related to overgrazing in the semi-arid southern caldenal area of Argentina. *Soil Science*, **166** (7), 441–452.