Aquifer recharge estimation at the Mesilla Bolson and Guaymas aquifer systems, Mexico

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Abstract. Three unsaturated profiles were obtained from Mesilla Bolson and Guaymas aquifer systems, northern Mexico. About 500 mL of undisturbed soil from depths between 1 m and 58 m below the surface were obtained every meter by dry percussion from a borehole located near Cd Juárez, Chihuahua state. The other two boreholes were located in the southwestern portion of Sonora state; about 500 mL of undisturbed soil from depths 0-5.50 and 0-8.50 m were obtained every 0.25 m by dry drilling at Narciso Mendoza and Guaymas sites, respectively. Samples were contained in sealed glass jars and analyzed for moisture content, chloride, deuterium and nitrate (NO_3-N). The interstitial water was extracted by elution; chloride and nitrate were determined by automated colorimetry while deuterium by direct reduction. Considering an average precipitation at Mesilla Bolson area of 230 mm/year, a chloride rain content of 1 mg/L and a mean Cl content on the unsaturated profile of 977 mg/L below the zero flux plane, we estimated by the Cl mass balance approach a net palaeorecharge in the area of about 0.24 mm/year with a probable time scale profile of 11,000 years. For the Guaymas area the net recharge is in the range 0.11-0.16 mm/year, assuming an average rainfall of 320 mm/year, Cl rainfall content of 3.4 mg/L and mean Cl concentrations on the profiles of 6,939 and 9,470 mg/L below the zero flux plane, respectively.

1. Introduction

During the last decades the use of groundwater has played a vital role on the socioeconomic development of the semiarid and arid areas of Mexico, especially in the northern part of the country where most of the industrial and urban areas relies only on the subsurface water resources.

The water tables around the major development areas of the north have been falling sharply as a result of the present scale of exploitation of groundwater recharged under more favorable climatic conditions, which amounts to the mining of the reserves. This has also resulted in the overexploitation of 97 out of 647 known aquifers of Mexico, which are mostly located in the northeastern, northern and central states of the country. It is an urgent matter to improve understanding of the origins of this groundwater, in particular whether it is being replenished.

Significant recharge at the regional scale in areas with mean annual rainfall below 250 mm/year is usually considered to be unlikely. However in areas with sandy soils and where rainfall intensity is favorable, infiltration may occur even in arid areas on an irregular basis.

Classical methods of recharge estimation based on physical methods are inappropriate in semi-arid/arid regions [1–4] because they have serious limitations. For example, the water balance approach relies on the small difference between rainfall and evaporation, two large numbers, to estimate the recharge. However, the measurement of these two processes has a lot of uncertainty.

The unsaturated zone under favorable conditions may have an important archive of information about water and solute movement, especially in Recent and Quaternary formations.

The isotopic composition and chemical constituents of water infiltrating through the unsaturated zone into the groundwater can be employed to determine the recharge, and contaminant behavior. For example, tritium profiles have been used in the semiarid and arid zones of Australia [5], India [6], Saudi Arabia [7] and Cyprus [8]. The radioactive isotopes ^{36}Cl and ^{3}H, released into the environment during the nuclear weapon tests of the late fifties and early sixties, are useful to investigate the water and solute movement in desert soils. The solute profile approach has been applied in Australia [9-11], Cyprus [8] and Senegal [12] to study the long term recharge, recharge history and water rock interaction.

The objective of this project was to develop an adequate methodology for the accurate determination of the sustainable replenishment of aquifers located in the arid and semiarid regions of northern Mexico and to estimate the long term recharge in pilot arid areas of northern Mexico.

This report presents the results obtained during the three year project duration by the Mexican mission: A description of the study areas, sampling (soil and rain water), analytical determinations (moisture content, chloride, deuterium and nitrate), experimental data and estimation of the recharge. The Mesilla Bolson (Conejos-Médanos) and the Guaymas aquifer systems, northern Mexico, were selected as pilot areas to estimate the recharge by mean of the unsaturated zone profile technique.

Overall the proposed three year programme was designed to contribute to the basic understanding of the fragile groundwater resources in northern Mexico so that informed decisions may be made for the sustainability and long-term management of groundwater on the region.

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2. Mesilla Bolson

2.1. Description of the study area

The study area is located in the vicinity of El Parabien ranch, at 40 km to the W of Cd Juárez and in the intersection of parallel 31°35' N-latitude and meridian 106°52' W-longitude (Figure 1). The ranch forms part of the Mesilla Bolson aquifer, which is located in the northern Mexican State of Chihuahua. Mean land surface elevation of Mesilla is 1,200 meters above sea level (masl). The area belongs to the Rio Bravo basin and it does not present natural channels or surficial water bodies within the Bolson.

According to the Köppen classification, the Mesilla Bolson has a dry climate, with maximum temperature in the summer of 38°C, minimum of −12°C in the winter and average of 17°C. The mean annual precipitation in the area is 230 mm and the rainy season is from July to September. Evaporation is high with a mean annual value reaching 2,400 mm.

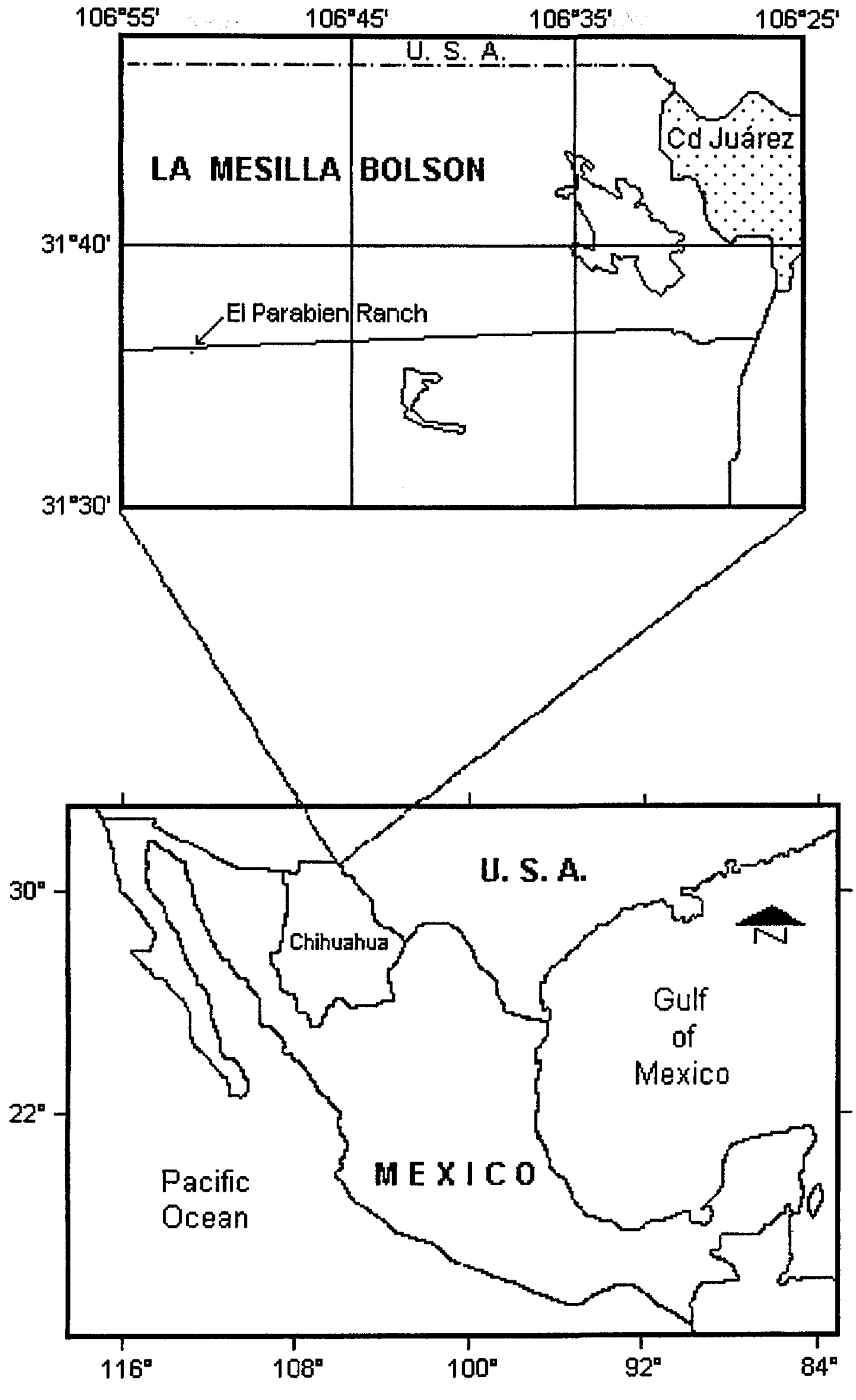

Figure 1. Location of Mesilla Bolson aquifer system.

The Bolson is located in the Basin and Range physiographic province [13] which is characterized by a major anticlinorium with Mesozoic limestones and Jurassic quartzites forming elongated ranges with a NW-SE trend [14]. The elongated limestone ranges have altitudes of 1,700 masl, topographically 550 m above the extensive intermountains valleys called Bolsons. The topography of the valleys is very smooth. The alluvial material filling the Bolsons consists mainly of clay and sand up to 800 m thick, and is overlaid by lacustrine clay deposits. The surface material is made up of Elias sand, in dunes up to 100 m thick, over which grows vegetation typical of semiarid areas: mesquites, palms, etc. The dunes are extensively distributed over the whole area.

The Mesilla Bolson aquifer is unconfined type, covers a total area of about 350 km^2 and is composed of alluvial deposits derived from the erosion of the intrusive and limestone rocks of the surrounding mountains. Winds reworked part of the surficial sediments forming the eolian deposits (dunes). The stratigraphic log of a well (300 m depth) located at 15 m of the drilling site indicates the predominance of fine sand with some clay and silt, and a thin layer of caliche (15-20 cm) at 1-3 m depth.

There are 23 shallow wells in the Bolson with depths lesser than 150 m; they are mainly used to cover the domestic and livestock requirements of the rural communities. In generally, their extraction rates are less than 1 L/s. Thus, the aquifer is still in natural conditions, but it has been considered the next water supply for Cd Juárez. The city has a population of one million people with a required water supply of more than 4 m^3/s. In 1988 the Secretaría de Recursos Hidráulicos (SRH), Water Resources Department, drilled 6 deep wells in order to explore the aquifer potential. The exploration wells reached 300 m depth.

Depth to the water table range from 50 to 90 m; total thickness of the unsaturated zone is about 60-70 m in the vicinity of El Parabien ranch (Figure 2).

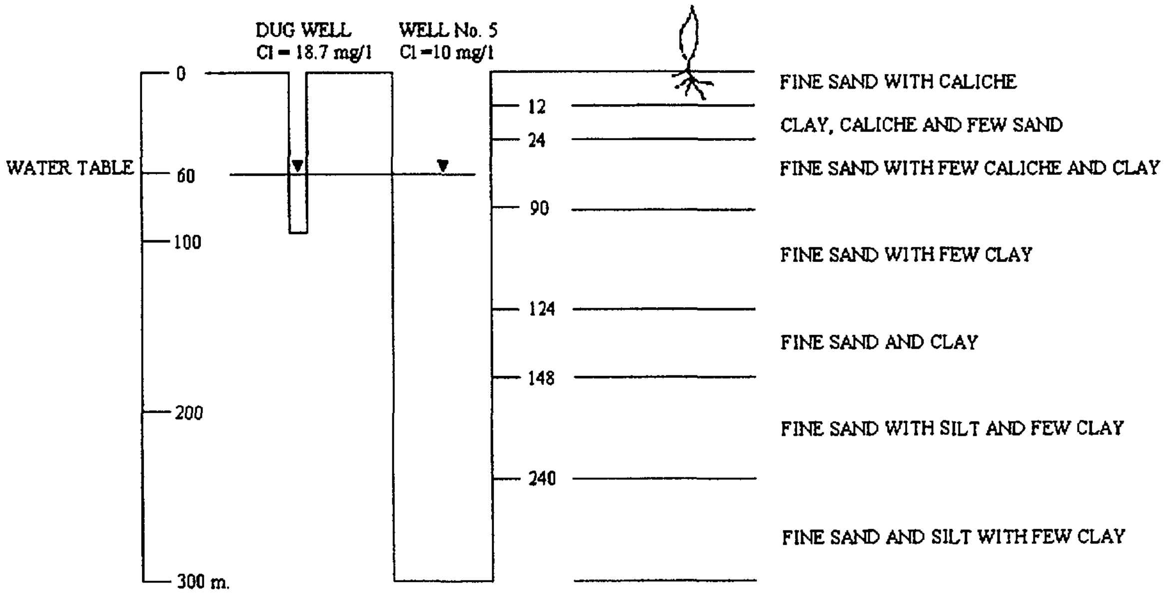

Figure 2. Schematic representation of the Parabien dug well and well No 5.

Groundwater has a predominant NE-SW flow direction. There is also a subsurface flow coming from the USA at the NW. The recharge area is located at the SW and the natural discharge of the aquifer is towards the Rio Bravo. The principal source of recharge is the locally infiltrated rainwater.

A summary of the hydrologic parameters of Mesilla Bolson aquifer system is shown in the next Table 1:

Table 1. Hydrogeologic parameters at Mesilla Bolson

Parameter	Representative value
Hydraulic gradient	0.0005 - 0.001
Transmissivity	2.0×10^{-3} m^2/s
Hydraulic conductivity	8.69×10^{-6} m/s
Effective porosity	0.09

The hydraulic gradient values reflect the slow groundwater movement in the area; transmissivity was estimated in the first 230 m of saturated thickness.

Total Dissolved Solids (TDS) range from 500 to 1,000 mg/L with an area distribution consistent with the principal flow direction. Groundwater is HCO_3-Ca and SO_4-Na types and in general its quality is good for human consumption. The low Cl content (10-19 mg/L) suggest that groundwater originates from recent infiltrated rain water. The chloride content at the Parabien dug well is 18.7 mg/L; this shallow groundwater sample was taken the 1st of November of 1996.

2.2. Sampling

2.2.1. Soil

A well was drilled in Mesilla Bolson, Chihuahua from January to June of 1997. The drilling equipment was a Longyear model 34 and the drilling technique was rotary for augering (2" of diameter) and dry percussion for soil sampling (split barrel of 2 1/2" id with sample retainer). Steel casing was necessary for side wall support. About 500 mL of undisturbed soil from depths between 1 m and 58 m below the surface were obtained every meter. Samples 9, 10, 12, 25, 27, 30, 33, 34, 35 and 37 were duplicated, while the interval 42-44 m depth were not sampled. This finally resulted in sixty four samples, which were immediately contained in sealed (with paraffin) glass jars to avoid moisture evaporation. The low moisture, null cementation and low compaction of the soil conditions originated great instability to the side walls of the borehole, which complicated the drive in steel casing and the soil sampling. Samples 1-40 were taken from January to May while samples 41-58 during the first week of June. According to the driller, samples from June were taken under excellent drilling conditions. We suspected an irregular procedure on samples 41-58. We finally decided to perform analysis to the whole set of samples.

2.2.2. Rain water

In august 1996 two rainfall sampling stations were installed (Tenite® Rain Gauge No 110672), Parabien station at 500 m of the drilling site and Cuarentenario station at 30 km from it. Local people collected samples. Fifty four and twenty rain samples from Parabien and Cuarentenario stations were collected, respectively

2.3. Analytical determinations

2.3.1. Soil

The sixty four soil samples were sent in June 1997 to the British Geological Survey (BGS) laboratory in Wallingford, UK, for analysis of Moisture Content, Cl, NO_3-N and δ^2H. CRP-funds were used to cover the corresponding costs.

2.3.1.1. Moisture content

One hundred grams of sample was heated at 70-80°C for 48 hours. The sample was then reweighted and moisture content determined as follows:

$$MC = \left[\frac{(P+W)-(P+D)}{(P+D)-P}\right] x100$$

where:

MC	moisture content (%)
P+W	wet weight of the sand plus beaker
P+D	dry weight of the sand plus beaker
P	weight of the beaker

2.3.1.2. Chloride and nitrate analysis

Fifty grams of the sample to be elutriated was weighed into a beaker, which had previously been washed and rinsed with deionised water. A 30 mL aliquot of deionised water was then added and after being thoroughly stirred, the sample was left for an hour. The supernatant solution was then decanted and filtered (0.45 µm) prior to analysis by automated colorimetry. Chloride and nitrate concentrations were then calculated using the following equation:

$$C = ((MC/(100/S)) + W/(MC/(100/S))) \text{ x elu}$$

where:

C	concentration of the anion in the interstitial water
MC	wet weight moisture content (%)
S	weight of sand (g)
W	volume of deionised water (mL)
elu	concentration of elutriate (mg/L)

2.3.1.3. Isotopic Analysis

Deuterium was analyzed using the direct reduction method [15]. The amount of sand holding 10 :L of water was calculated for each sample on the basis of the dry weight moisture content.

This amount was inserted into a deuterium finger vessel with about 1g of zinc shot at the base and a plug of glass wool approximately half way up. The sand rested on the glass wool to prevent the full effects of reaction heat (500°C) on the minerals and organic compounds in the sand. The reaction tubes were frozen in liquid nitrogen, evacuated and reacted in a hot block for one hour.

After cooling, the vessels were attached to a VG Optima Mass Spectrometer with an automatic inlet manifold for analysis [16,17]. Results are reported relative to V-SMOW. Analytical precision varies with the original moisture content of the sample.

2.3.2. Rain

Seventy four rain samples were collected by local people. Analytical determinations were performed in local laboratories. Rain samples 1-19 from Parabien and 1–20 from Cuarentenario were analyzed in the laboratory of Junta Municipal de Aguas y Saneamiento (JMAS) of Ciudad Juárez, Chihuahua; samples 19-55 in the laboratory of El Paso Texas. After one year of operation, the Cuarentenario station was closed down due to logistic problems. The 1–19 rain chloride concentrations at the Parabien station range from less than 0.5 to 29.8 mg/L. The initial high values were attributed to rain water evaporation and to the high detection limit (5 mg/L) of the analytical technique applied by JMAS. That was the main reason to change of laboratory and to insist with the local people to collect the rain samples immediately after a rain event. The Cl concentrations of rain samples 20–54 range from 0.5 to 2.8 mg/L. Published data about rain Cl content in the New Mexico area [3, 18–21] range from 0.24 to 0.63 mg/L, so the Cl concentrations at El Parabien ranch should range from less than 0.5 to 2.8 mg/L. The analytical techniques used by the JMAS and El Paso laboratories were Argentometric (detection limit of 5.0 mg/L) and Ion Chromatography Method (detection limit of 0.5 mg/L).

2.4. Rain isotopic data from Chihuahua (IAEA) station

The rain isotopic data from GNIP-Chihuahua station (7622500) were taken as input data for Mesilla Bolson and Guaymas aquifer systems. The station is located 400 km south of Cd Juárez, at 28.63° N and 106.07° W, with an altitude of 1,423 mamsl. The 125 pair of δ^2H and δ^{18}O data from the period 1962–1988 were used to obtain the Local Meteoric Water Line (LMWL):

$$\delta^2\mathrm{H} = 7.13 \cdot \delta^{18}\mathrm{O} + 2.78 \quad (r^2 = 0.937,\ n = 125)$$

which were compared with the Global Meteoric Water Line (GMWL):

$$\delta^2\mathrm{H} = 8 \cdot \delta^{18}\mathrm{O} + 10 \quad (\mathrm{VSMOW})$$

2.5. Evaluation

The lithological characteristics of the soil profile extracted from the sixty-four samples is as follows (Table 2): The sediments of this profile are rather heterogeneous as shown from the geological details and display a wide range of moisture contents: sandy horizons have 2–4% moisture, but clay-rich horizons contain up to 15–20% (Table 3). The δ^2H data show some evidence of the typical isotopic enrichment encountered close to the surface in arid zone profiles (Figure 3). Below this, a local peak in δ^2H at 8–9 m may be related to the presence of clay minerals, though such an effect is not apparent further down the profile where clays are present. A steady state of around -60λ extends from approximately 10 m to 35 m below the surface. Below this, there is a fairly abrupt change to a composition with more 'noise' but averaging around -35λ. This coincides with consistently low moisture content and chloride concentration.

Table 2. Lithological characteristics of the soil profile

Depth (m)	Description
1	Unconsolidated powdery sand. Mainly very fine to fine grained. Light brown colour.
2–4	Unconsolidated powdery sand. Very fine to fine grained. Small grit sized particles within main matrix. Very light beige colour.
5	Unconsolidated sand. Grain size range from very fine to very coarse including small pebbles. Grains are individually multi-coloured but overall grey brown colour. Mica flakes present.
6–8	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
8–9	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
10–11	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
12–13	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
14–18	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
19	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
20–22	Unconsolidated powdery sand. Very fine to fine grained. Very light beige colour.
23–27	Light brown, semi-consolidated, non-indurated sediment.
28–30	Unconsolidated powdery sand. Very fine to fine grained. Small grit sized particles within main matrix. Very light beige colour.
30	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
31–32	Unconsolidated, loose, fine to medium grained sand. Dark beige colour due to occurrence of black sand grains.
33–37	Light "chocolate" brown mudstone / clay, semi-consolidated, non-indurated sediment.
38–47	Unconsolidated, loose, fine to medium grained sand. Dark beige colour due to occurrence of black sand grains.
48–58	Unconsolidated sand, well-sorted, mainly medium to coarse grained. Light brown colour with slight reddish tinge.

Table 3. Analytical results of Mesilla Bolson, Chihuahua

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
1.0	3.31	61.09	6.35	-61
2.0	3.49	1333.06	< 0.1	-71
3.0	2.74	1664.10	< 0.1	-69
4.0	1.06	4555.76	< 0.1	-65
5.0	2.94	743.98	< 0.1	-56
6.0	2.06	368.56	< 0.1	-54
7.0	5.24	177.37	0.44	-51
8.0	8.22	84.67	0.12	-52

Table 3. (cont.)

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
9.0	10.01	756.64	1.78	-56
9.0	17.02	1230.83	< 0.1	-62
10.0	2.60	287.27	1.95	-63
10.0	2.35	459.41	2.52	-64
11.0	1.27	802.31	< 0.1	-62
12.0	18.64	1079.87	0.40	-63
12.0	15.40	1485.31	2.89	-62
13.0	17.36	619.54	< 0.1	-60
14.0	8.87	774.28	3.71	-60
15.0	4.39	375.23	< 0.1	-63
16.0	1.77	519.69	< 0.1	-58
17.0	1.37	798.61	< 0.1	-60
18.0	11.45	1317.27	0.79	-60
19.0	12.70	1227.39	1.75	-61
20.0	3.51	574.07	< 0.1	-65
21.0	1.83	681.24	< 0.1	-56
22.0	1.74	920.13	< 0.1	-58
23.0	6.13	796.24	< 0.1	-51
24.0	6.73	1135.94	-	-60
25.0	8.36	1042.68	< 0.1	-56
25.0	19.32	3186.27	5.83	-59
26.0	19.04	3042.56	-	-64
27.0	21.01	2657.83	6.53	-67
27.0	19.25	2781.84	-	-65
28.0	3.64	623.90	< 0.1	-61
29.0	9.54	224.87	< 0.1	-58
30.0	2.81	1783.41	5.35	-62
30.0	16.43	1345.57	2.59	-61
31.0	1.53	431.95	1.67	-58
32.0	2.35	292.60	< 0.1	-55
33.0	27.13	1220.09	-	-66
33.0	18.17	755.58	6.21	-64
34.0	17.22	117.72	10.57	-60
34.0	15.39	809.66	6.49	-61
35.0	16.59	848.73	6.53	-58
35.0	22.32	1390.22	10.35	-63
37.0	15.06	1123.99	8.68	-59
37.0	10.69	598.43	4.95	-59
38.0	1.63	275.76	< 0.1	-50
39.0	1.94	318.78	< 0.1	-51
40.0	1.00	238.29	< 0.1	-46
41.0	0.97	289.71	< 0.1	-49
45.0	1.90	637.21	8.33	-37
46.0	2.93	334.92	3.39	-50
47.0	2.67	263.27	< 0.1	-44
48.0	2.45	263.00	< 0.1	-42
49.0	2.90	229.13	< 0.1	-38
50.0	2.07	247.63	0.98	-37
51.0	2.39	235.94	< 0.1	-42

Table 3. (cont.)

Depth (m)	M.C. (%)	Cl (mg/L)	NO_3-N (mg/L)	δ^2H (‰)
52.0	2.57	313.10	< 0.1	-50
53.0	1.65	261.14	< 0.1	-48
54.0	2.73	253.20	< 0.1	-34
55.0	2.13	241.00	< 0.1	-46
56.0	4.55	317.77	< 0.1	-47
57.0	3.94	171.94	< 0.1	-41
58.0	2.27	407.99	< 0.1	-55

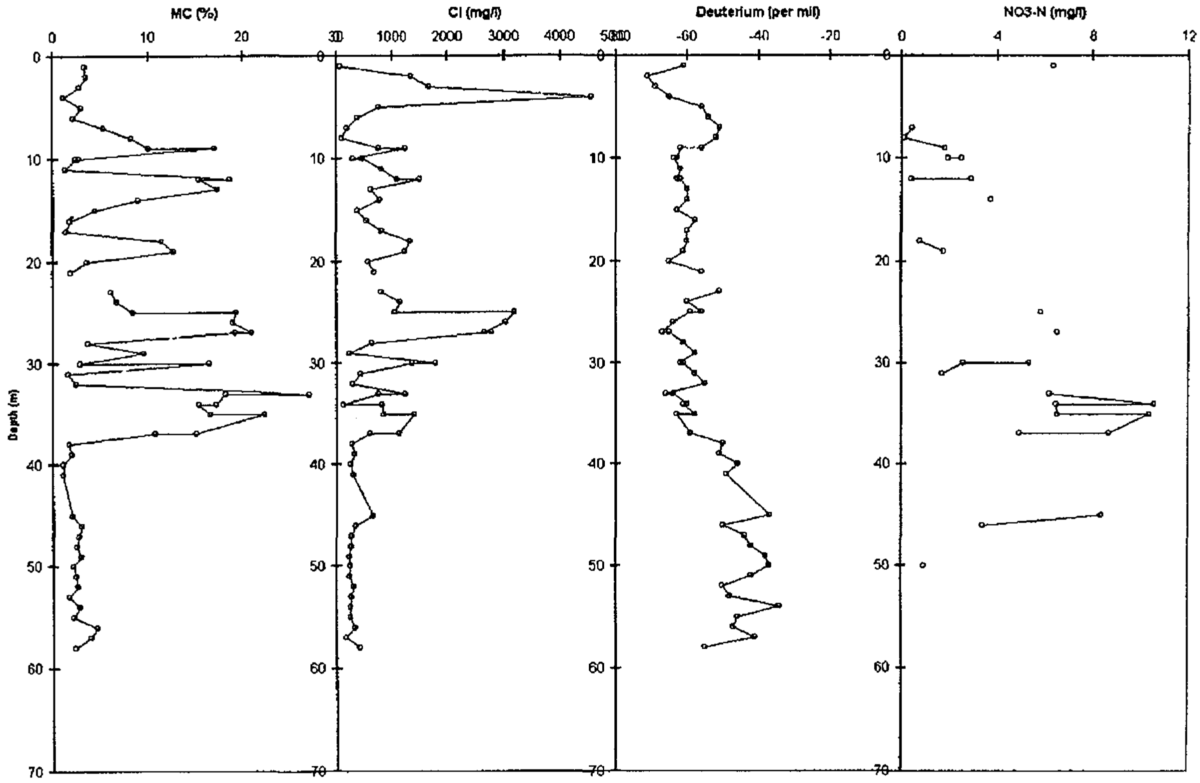

Figure 3. Unsaturated profiles from Mesilla Bolson, Chihuahua State, Mexico.

The chloride profile displays also a typical marked enrichment close to the surface and at 25–27 m below the surface (Figure 3). The latter coincides with a clay-rich horizon containing up to 21% of moisture content. Finally, the NO_3-N data shows no significant trend.

A summary of the analytical results is shown in the following Table 4:

Table 4. Summary of the analytical results from 1 to 58 m depth.

Parameter	Range	Average
MC (%)	0.97 to 27.13	7.63
Cl (mg/L)	61 to 4560	858
δ^2H (‰)	-71 to -34	-56
NO_3-N (mg/L)	0.1 to 10.57	4.28

The evaluation of the recharge rate at Mesilla Bolson aquifer, based on the chloride mass balance and applied to the 8–40 m depth interval (below the zero flux plane and disregarding the 41–58 m noise data), is of 0.24 mm/year considering an average rainfall of 230 mm/year, a value of 1 mg/L of Cl in rainfall and a mean concentration of 977 mg/L in the Cl profile. It is possible that the timescale of the profile represents some 11,000 years. If we consider the whole profile, the estimated recharge in the area would be 0.27 mm/year and the time scale of 17,000 years.

Table 5. Summary of the analytical results from 8 to 40 m depth

Parameter	Unsaturated Zone		Groundwater
	Range	Average	
MC (%)	1.0 to 27.13	10.09	
Cl (mg/L)	85 to 3,190	977	10 to 19
δ^2H (‰)	-67 to -46	-59.5	-65.5 to –49.8 [14]
NO_3-N (mg/L)	0.12 to 10.57	4.36	
^{18}O ($^{0}/_{00}$)			-7.7 to –4.8 [14]

The average Cl concentration in the unsaturated zone is 2 orders of magnitude higher than the average Cl content found in the groundwater. This could be due to recharge originated in other areas and transported by the regional groundwater flow or to the bypass flow of the locally infiltrated rain water.

From Figure 4, it can be observed an evaporation effect at LMWL with respect to GMWL. The intersection of both lines is at the point ($\delta^{18}O$ = -8.32, δ^2H = -56.57), which is close to the local groundwater values. On the other hand, the interstitial water data of δ^2H (Table 5) are in the range –71 to –34 ‰ so we can expect $\delta^{18}O$ data in the range of –35 to –10 ‰. Both, the interstitial water and the groundwater data are waters of recent infiltration, geologically speaking.

The estimated recharge and unsaturated profile data of El Parabien ranch are consistent with the published data of El Hueco Bolson, Texas [18–20], located 100 km east of Mesilla Bolson, Chihuahua, where the US Government pretend to install a low radioactive waste disposal site.

In order to determine the concentration peak of ^3H in the unsaturated zone of Mesilla Bolson aquifer system and the recharge variability (spatial and temporal) in the area, a hand augering campaign (dry drilling) was performed during the first semester of 1998. In all the tested places the caliche layer appeared at 2–3 m depth which caused to stop the hand drilling. From the 24th of July to the 1st of August of 1998, a new hand drilling process was initiated. The new site was located at about 400 m from the initial one. The first activity was to drill across the caliche layer, which took two full days of work. Dry drilling was very difficult and slow due to the low moisture content of the soil. This also produced high instability on the sidewalls of the hole, so it was necessary to case (PVC) the hole. Soil samples were taken every 0.25 m depth; drilling was stopped after reaching only three meters depth, because the sand auger got fissured due to the very dry soil conditions. Dr Edmunds suggested to look for an alternate area: Mexicali at Baja California state or Guaymas at Sonora state. Several places of Mexicali were also tested during July 1997; drilling was not possible due to the presence of small pebbles on the soil profile and to the extreme dry soil conditions (average rain of 60 mm/year).

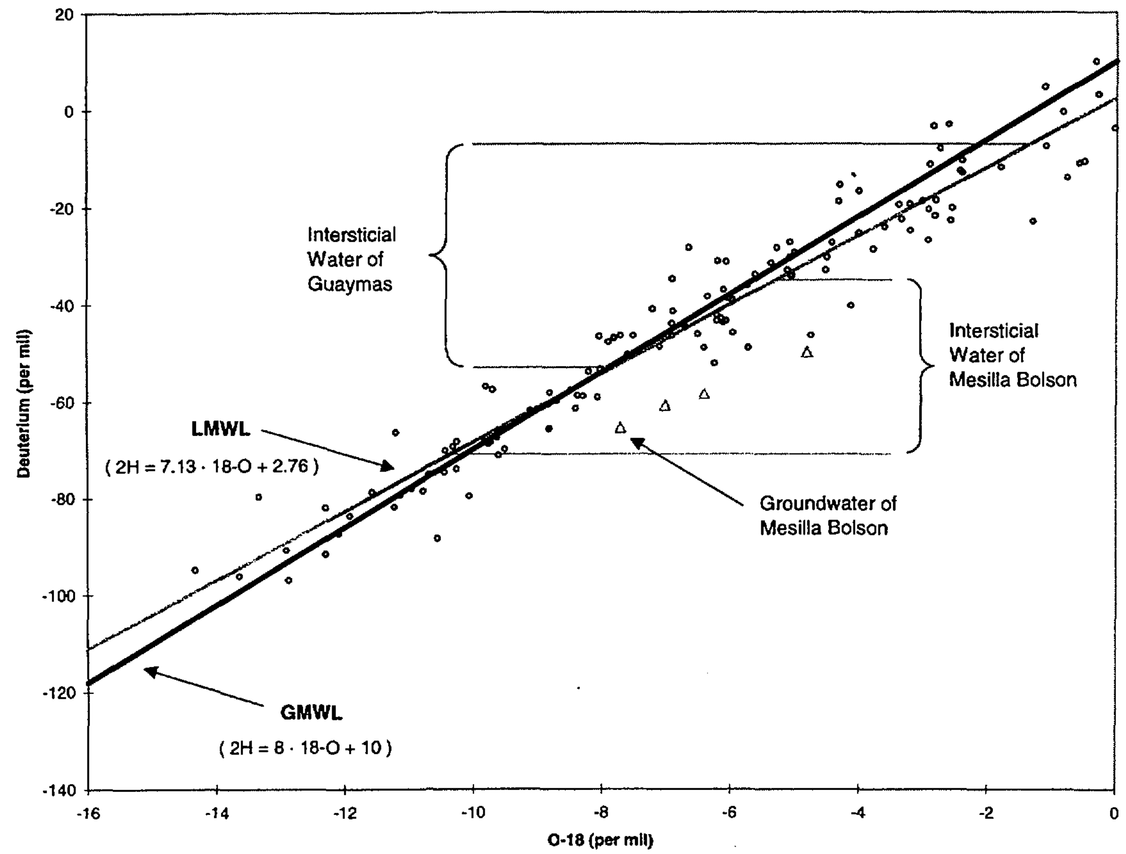

Figure 4. Global and local (Chihuahua IAEA station) meteoric water lines.

Table 6. Comparison of data of Mesilla and Hueco Bolsons

Description	El Hueco Bolson Texas	Mesilla Bolson Chihuahua
Precipitation (mm/year)	280	230
Depth to water table (m)	150	60-65
Caliche layer (m)	1-2	1-3
Cl rain (mg/L)	0.40 to 0.63	0.5 to 2.8
Recharge rate (mm/year)	0.01 to 0.7	0.24
Maximum Cl (g/m^3)	9,300	4,560
Time scale (years)	10,000 to 30,000	11,000
Depth to tritium peaks (m)	0.0, 0.6, 1.4	?

During the drilling process at the new site we observed the presence of roots and small channels or tubes of carbonates below the caliche layer. The water that infiltrates through the caliche layer dissolves the caliche and forms small channels (tubes) through which the water could move faster vertically downgradient. This could explain the bypass flow ($Cl_{gw} < Cl_{uz}$). However, the extreme dry conditions of the soil suggest that water movement through the unsaturated zone is very slow and therefore the results of the chloride profile technique are more realistic for the study area. The low Cl content found in the upper part of the aquifer (Parabien dug well) could be due to a regional groundwater flow from external areas. More information is required to define the recharge mechanisms.

3. Guaymas

3.1. Description of the study area

The study area is located in the semiarid region of the Guaymas Valley. The valley is an important coastal area located in the southwestern portion of the Sonora state, Mexico (Figure 5), between 27°53' and 28°50' latitude N and 110°15' and 111°10' longitude W. The mean elevation of the area is 50 mamsl. The main cities are Guaymas and Empalme, which had a total population of 233,798 inhabitants in 1990.

The Guaymas Valley is part of the lower sub-basin of the Matape River and covers an area of 5,700 km^2 with a north-south trend. The Matape River controls drainage processes within the basin; the river is only active during the rainy season and has an average discharge of 35 Mm^3/year.

The main economic activities are fishing, agriculture, cattle raising, and tourism. Groundwater represents the main source of water for the municipal and agricultural activities of the area. Thirty four percent of the 28,000 ha dedicated to agriculture are subject to irrigation.

The climate of this region is classified as semiarid and it is characterized by high temperature and low precipitation. Temperature ranges from 15°C to 30°C, with an average of 25°C on the period 1966–1986. Mean annual precipitation is 320 mm while potential evaporation rates reach 2,600 mm/year [22]; precipitation events are intense but short-lived and they occur primarily during late summer - early autumn.

The valley is composed of grabens and dikes, trending from north to south, which resulted from tectonic activity over the Tertiary basal deposits of granitic and andesitic rocks of the Cretaceous Period [23]. Quaternary detritus eroded from the adjacent ranges progressively filled the valley.

The Quaternary deposits of the valley provide excellent pathways for deep percolation and recharge. High porosity and permeability characterize the sand alluvial deposits. These sand layers cover the central and upper portion of the aquifer. Their saturated water thickness has been estimated to be 200 m under steady state conditions [24–27]. The piedmont deposits of the northern portion consist mainly of gravel, silt and sand. A thick shale of marine origin called "Blue Clay" separates the regional aquifer into an unconfined and a semi-confined unit [25]. The unconfined unit occurs near the margins of the valley and has a saturated thickness of up to 190 m [27], which increases towards the center of the valley. The confined aquifer extends approximately from Ortiz Levee to Maytorena.

The hydraulic conductivity ranges from 3×10^{-4} to 1.5×10^{-5} m/s for the unconfined unit. The specific yield has been assigned a value of 0.12 [26]. Specific capacities of the wells completed within this unit are between 9 and 100 L/s/m [27]. For the semi-confined unit, the transmissivity values range from 2.2×10^{-3} to 5.0×10^{-3} m^2/s, with a storage coefficient of about 10^{-4}. Mean specific capacity for the semi-confined unit is about 12 L/s/m.

Groundwater flow under natural conditions was from inland towards the coast (north to south); the aquifer was discharging fresh water into the Gulf of California (Figure 6). Heavy groundwater abstraction for agricultural use started in 1950, reversing the natural hydraulic gradient. As a result, seawater intruded the fresh water aquifer deteriorating the groundwater quality and impacting water usage for municipal and industrial activities. Several wells and adjacent farming areas had to be abandoned.

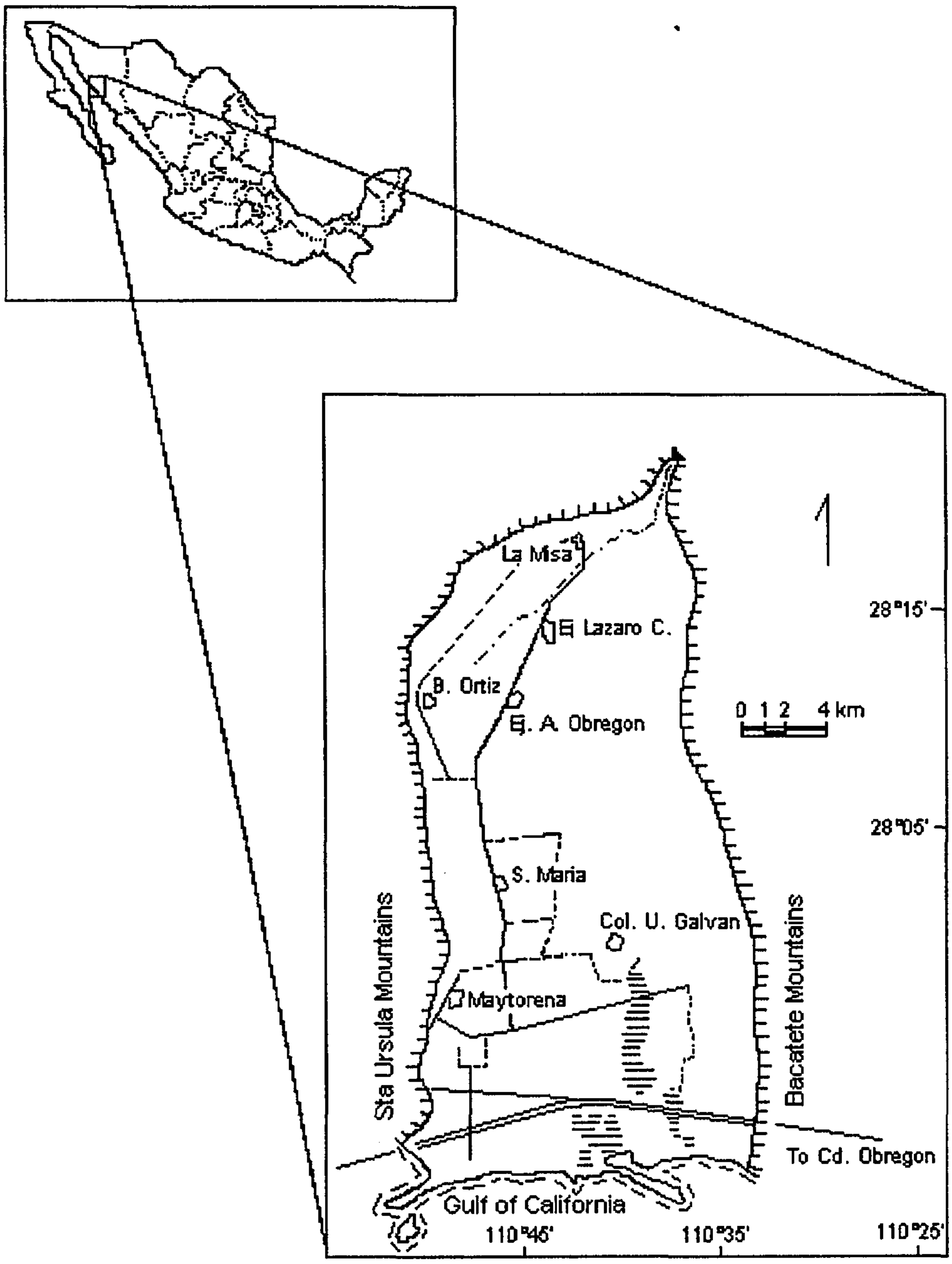

Figure 5. Location of Guaymas aquifer, Sonora state.

Groundwater discharge through the 250 active wells (completed mainly in the unconfined unit) is about 185 Mm^3/year while the estimated natural recharge is of 100 Mm^3/year. Groundwater abstraction reduction has been recommended since 1967 without success [22, 24, 25]. As a result, depth to water table during the 1990–1991 season ranged from 25 to 120 m, with an average of 82 m [28]. Maximum depths were observed near Maytorena town and to the west of Santa Maria de Guaymas. Maximum water table elevation reached 55 meters below mean sea level.

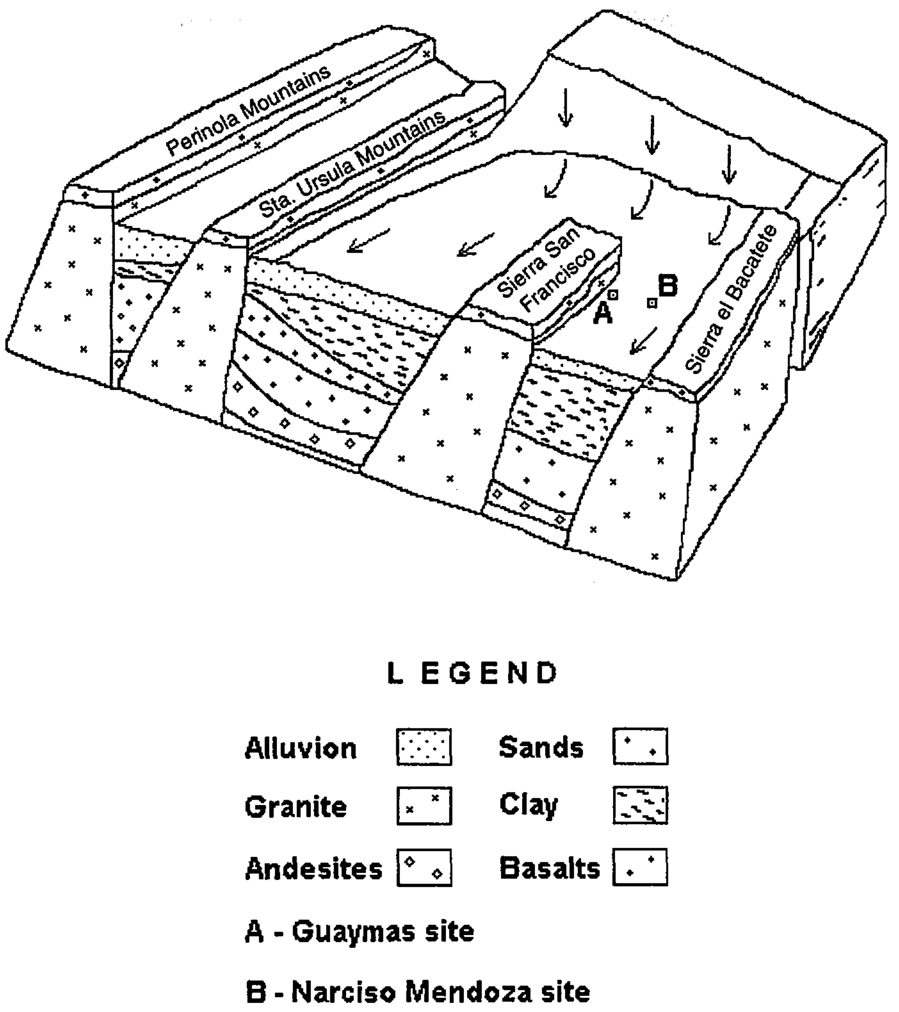

Figure 6. Groundwater flow system under natural conditions at Guaymas aquifer

Recharge at Guaymas aquifer occurs due to different mechanisms: (1) horizontal flow from the Upper Matape Basin, (2) vertical recharge at the alluvial fans of the northern portion of the area, (3) river leakage from the Matape River during the rainy season, and (4) areal discharge over the valley. It is estimated that between 20 and 30% of the irrigation volume becomes deep percolation. An upward component of flow through the "Blue Clay" is thought to contribute with 10 Mm^3 to the water balance of the unconfined aquifer [22].

The water quality of the aquifer has changed as a result of changes in natural groundwater flow. The saline front has reached wells located at 10-12 km from the coastline. TDS values range from 6,000 to 300 ppm. Sodium and chloride concentrations decrease from near the shore towards the center of the valley (1,100 to 460 mg/L for chloride; 529 to 207 mg/L for sodium). Increase in chloride content from background levels (90 mg/L) confirms seawater intrusion in response to heavy pumpage at the Guaymas aquifer. A zone of good water quality is found near the town of Mi Patria es Primero where chloride concentrations are about 71 mg/L.

The groundwater quality at the Cruz de Piedra region, eastern part of the aquifer, experiences a different seawater influence because of the lesser abstraction rates than the western portion of the aquifer.

3.2. *Sampling*

3.2.1. Soil

Twenty eight geologic samples from the Guaymas Valley were taken by dry drilling from the 9th to the 11th of February of 1999 at two sites: 11 from the Narciso Mendoza site and 17 from the Guaymas site (Table 7). The UTM coordinates of Narciso Mendoza are 545 100 and 3 100 308 while for Guaymas site are 541 806 and 3 098 717 (Figure 5). About 500 mL of undisturbed soil were obtained every 0.25 m. Samples were obtained with a Dormer™ sand auger, transposed to plastic bags from where were immediately contained in sealed (with paraffin) glass jars. Drilling was stopped after reaching 5.50 m depth at Narciso Mendoza site and 8.50 m depth at Guaymas site, due to the presence of hard strata or gravels in the soil profile. At least 4 or 5 sites were tested before the successful drillings described above.

3.3. *Analytical determinations*

The twenty eight soil samples were sent in March 1999 to the British Geological Survey (BGS) laboratory in Wallingford, UK, for analysis of Moisture Content, Cl, NO_3-N and δ^2H. CRP-funds were used to cover the corresponding costs.

3.4. *Evaluation*

3.4.1. Narciso Mendoza site

The sediments of the profile consist mainly of quaternary sands. The sands show an increase in the gravel content at the interval 2.25–3.00 m depth and an increase in the clay content at 3.75–4.50 m depth.

The MC values (Table 7) found close to the soil surface show the evaporation effects, while the average MC is of 6.16% (Figure 7). The minimum and maximum values are found at 2.25–3.00 and 3.75–4.50 m depths, which are associated with layers with coarser and finer sediment content, respectively. Below the 3.75–4.50 interval, the MC decreases to average values.

Table 7. Analytical results of Guaymas, Sonora

Top Depth (m)	Bottom Depth (m)	M.C. (%)	Cl (mg/L)	NO_3 (mg/L)	δ^2H (‰)
Guaymas site					
0.25	0.50	3.57	23,972.10	222.11	-13
0.75	1.00	5.95	11,901.92	53.98	-7
1.25	1.50	7.11	6,227.93	20.51	-11
1.75	2.00	10.50	13,124.03	66.39	-15
2.25	2.50	10.92	15,269.98	38.12	-25
2.75	3.00	10.30	11,693.16	20.63	-21
3.25	3.50	10.05	10,112.43	16.04	-29
3.75	4.00	10.99	11,825.38	19.16	-29
4.25	4.50	12.92	12,061.39	21.05	-30

Table 7. (cont.)

Top Depth (m)	Bottom Depth (m)	M.C. (%)	Cl (mg/L)	NO_3 (mg/L)	δ^2H (‰)
4.75	5.00	12.43	13,474.52	22.35	-34
5.25	5.50	9.73	12,713.08	26.43	-26
5.75	6.00	11.78	11,236.58	15.57	-23
6.25	6.50	9.95	5,332.40	9.82	-34
6.75	7.00	8.01	5,922.58	11.80	-36
7.25	7.50	6.11	3,405.73	6.65	-28
7.75	8.00	3.52	3,482.14	15.48	-44
8.25	8.50	2.57	6,170.48	22.67	-53
Narciso Mendoza site					
0.50	0.75	6.55	13,679.26	92.39	-4
0.75	1.00	8.51	8,505.10	38.88	-5
1.25	1.50	7.40	6,491.56	4.86	-12
1.75	2.00	4.65	7,866.41	7.55	-29
2.25	2.50	2.55	7,408.40	7.10	-29
2.75	3.00	3.01	2,376.89	1.10	-27
3.25	3.50	5.28	7,349.56	2.89	-30
3.75	4.00	9.36	9,437.74	1.13	-30
4.25	4.50	8.60	7,289.98	2.31	-27
4.75	5.00	7.28	8,513.07	1.22	-20
5.25	5.50	4.58	5,719.83	2.86	-24

The Cl content depicts a typical marked enrichment close to the surface; below this, there is steady state around 7,300 mg/L with some variations, which include the coarser sediments of the profile where the minimum values are present.

The δ^2H data show the typical isotopic enrichment encountered close to the surface in arid zone profiles. Below this, there is a steady state around –28%, with a local peak at 5.0 m depth.

Nitrate profile shows the elevated values found at the upper soil zone beneath uncultivated areas [29]. Below 2.75 m there is steady state at about 2.10 mg/L.

3.4.2. Guaymas site

The lithology of this profile is as follows: from 0.25 to 6.0 m the sediments are Quaternary sands mainly with a light increase in the finer sediment content at the intervals 1.75-2.50 m and 4.25-5.00 m depth; from 6.0 to 8.50 the sediments show an increase in the gravel content. The moisture content values depict the evaporation effect found at the soil surface (Figure 8). From 1.75 to 6.00 m there is an steady state of around 11%, and form 6.00 to 8.50 the MC experience an decreasing trend up to a minimum of 2.57%, due to the presence of coarser sediments.

The Cl profile displays also a typical marked enrichment close to the surface. From 1.75 to 6.00 m depth, there is a steady state of around 12,000 mg/L. Below this, the Cl profile experience a shift towards a new steady state of around 5,000 mg/L, which is associated with coarser sediments.

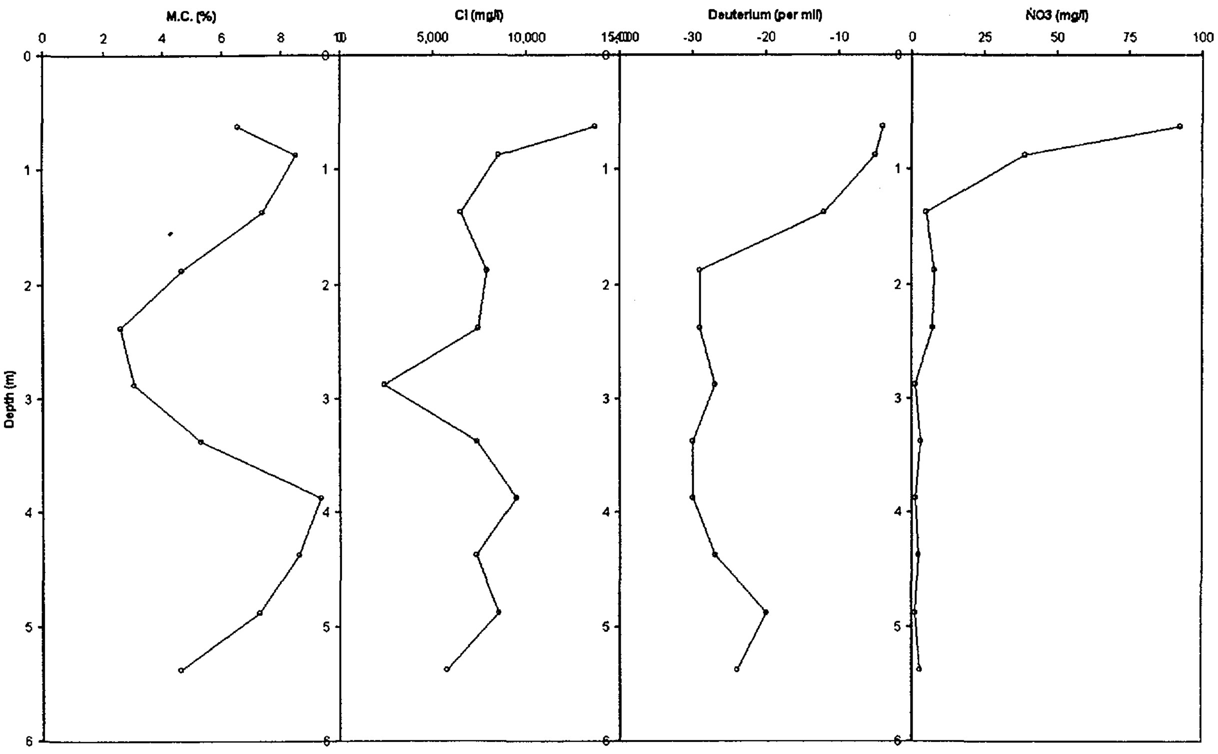

Figure 7. Unsaturated profiles from Guaymas site, Sonora State, Mexico.

The deuterium profile also shows some evidence of the typical isotopic enrichment encountered close to the surface in arid zone profiles (Figure 7). A general depletion tendency is observed along the profile, although it can be observed a quasi steady state from 2.25 to 7.50 m depth at a value of –29%.

Nitrate profile also shows elevated values at the top. At the 1.75 m there is a local peak associated with the finer sediments of this stratum. From 2.75 to 5.50 there is a steady state of around 20 mg/L, and below this, nitrate values show a decreasing trend and finally a content increase before reaching the bottom portion.

A summary of the analytical results is shown in the next Table 8:

Table 8. Summary of the analytical results from Guaymas aquifer

Parameter	Range	Average
	Guaymas site	
MC (%)	2.57 to 12.92	8.61
Cl (mg/L)	3,406 to 23,972	10,466
δ^2H (‰)	-53 to –7	-27
NO_3-N (mg/L)	6.65 to 222.11	35.81
	Narciso Mendoza site	
MC (%)	2.55 to 9.36	6.16
Cl (mg/L)	2,377 to 13,679	7,694
δ^2H (‰)	-30 to –4	-22
NO_3-N (mg/L)	1.10 to 92.39	14.75

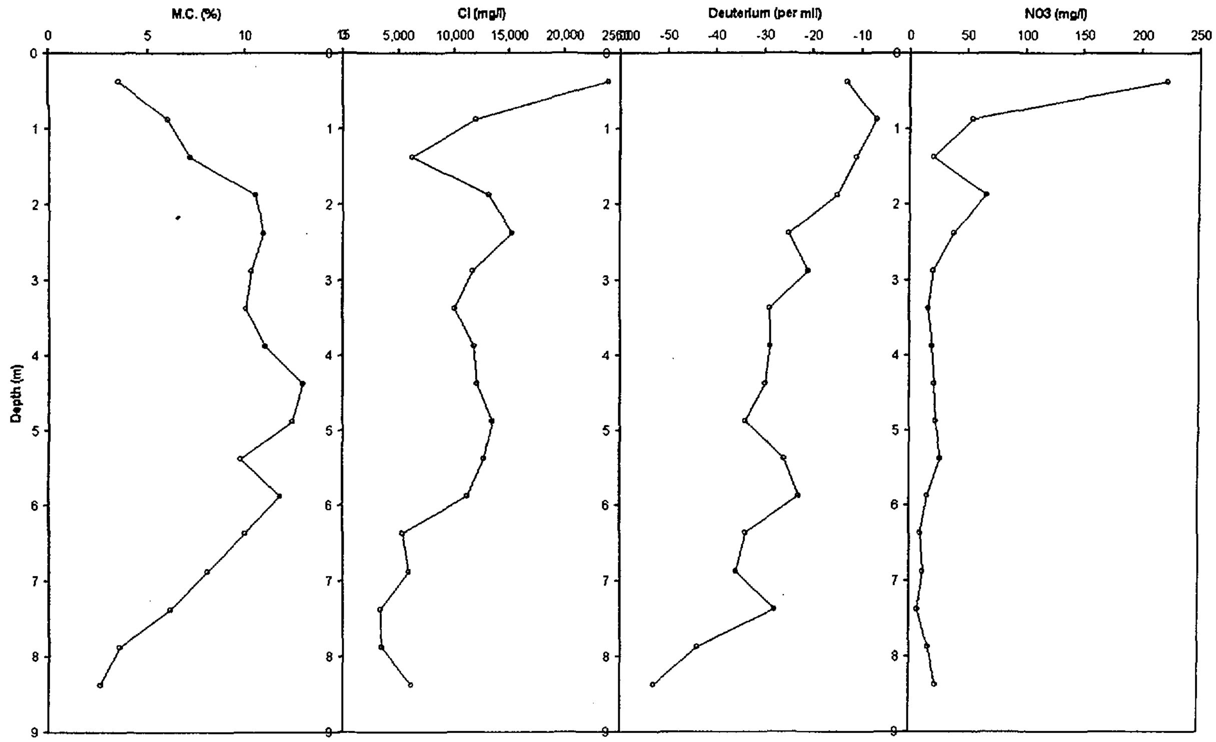

Figure 8. Unsaturated profiles from Narciso Mendoza site, Sonora State, Mexico.

A rain analysis performed by the Instituto Tecnolǒgico de Sonora showed a Cl rain content in the area of 3.47 mg/L. According to Ref. [21], the Cl rain concentration in the coastal areas of California, USA, is about 3.31 mg/L. More rain samples need to be obtained in this area in order to corroborate the Cl content in the rain.

Recharge rate evaluation at Narciso Mendoza and Guaymas sites, based on the chloride mass balance and applied to the 1.25-5.50 and 1.25–8.50 m depth intervals, are of 0.16 and 0.11 mm/year, respectively. The latter assumes an average rainfall of 320 mm/year, a value of 3.4 mg/L of Cl in rainfall and mean Cl concentrations on the profiles of 6,939 and 9,470 mg/L below the zero flux plane (1.25 m depth), respectively.

The Cl concentrations in the unsaturated zones are considerable higher than those found at the groundwater. This means that the areal recharge over the valley is insignificant compared with other recharge mechanisms: horizontal flow, alluvial fans and river leakage. The estimated recharge values represent 0.04-0.05% of the total rain.

The lower part of the Guaymas site profiles experience a MC and Cl content decrease, deuterium depletion and a nitrate content increase which could be due to a different recharge mechanism. The site is located at less than 1 km from the San Francisquito hills. During the drilling process we reached a hard stratum that represents the contact between the hard rock and the Quaternary sediments. This contact layer could represent a preferential path for water infiltrated at the hill or in the alluvial fan. That could explain the relative lower Cl content, higher nitrate concentrations and the depletion of deuterium.

No information about the groundwater isotopic content was available. The interstitial water data of δ^2H (Table 7) on both sites are in the range –53 to –7 ‰ so we can expect $\delta^{18}O$ data in the range of –8 to –1 ‰ (Figure 4).

4. Publication

The results of the first year project activities were orally presented at the XXIII General Assembly of the European Geophysical Society, celebrated at Nice France from 20-24 of April, 1998 (Session HSA6 Hydrology and soil processes .1 Recent advances in tracers in vadose zone hydrology: Tuesday 21 April 1998). The title of the presentation was “Recharge Estimation at the Conejos-Medanos aquifer system, Northern Mexico”.

5. Conclusions and recomendations

The recharge rate at Mesilla Bolson aquifer systems is about 0.24 mm/year; Future aquifer exploitation should be based on the non renewable water resources.

For the Guaymas aquifer system estimated recharge values represent 0.04-0.05% of the total rain which means that the areal recharge over the valley is insignificant compared with other recharge mechanisms.

More information about the chemical and isotopic content of the unsaturated zone and the groundwater in both studied areas is required in order to discern about the groundwater recharge mechanisms and the spatial variability of the areal recharge.

It is recommended to continue the chemical determination of rainfall in the area, in order to know the input values of the recharge for the regional aquifers.

The solute profile technique is potentially important for investigating the unsaturated zones of arid and semiarid regions of northern Mexico, and for estimating recharge of aquifers of northern Mexico, providing input data for chloride is available (Edmunds *et al.*, 1988).

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