Conceptual hydrogeological model of volcanic Easter Island (Chile) after chemical and isotopic surveys

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Abstract Most human activities and hydrogeological information on small young volcanic islands are near the coastal area. There are almost no hydrological data from inland areas, where permanent springs and/or boreholes may be rare or nonexistent. A major concern is the excessive salinity of near-the-coast wells. Obtaining a conceptual hydrogeological model is crucial for groundwater resources development and management. Surveys of water seepages and rain for chemical and environmental isotope contents may provide information on the whole island groundwater flow conditions, in spite of remaining geological and hydrogeological uncertainties. New data from Easter Island (Isla de Pascua), in the Pacific Ocean, are considered. Whether Easter Island has a central low permeability volcanic "core" sustaining an elevated water table remains unknown. Average recharge is estimated at 300–400mm/year, with a low salinity of 15–50mg/L Cl. There is an apron of highly permeable volcanics that extends to the coast. The salinity of near-the-coast wells, >1,000mg/L Cl, is marine in origin. This is the result of a thick mixing zone of island groundwater and encroached seawater, locally enhanced by upconings below pumping wells. This conceptual model explains what is observed, in the absence of inland boreholes and springs.

Keywords Island hydrology · Volcanic aquifer · Conceptual model · Easter Island · Chile

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Introduction

The geological and hydrogeological structure of many volcanic islands (for example, Réunion (Indian Ocean), Hawaii archipelago and Tahití (Pacific Ocean), Madeira, Cape Vert Islands, Canary Islands, and the Azores (Atlantic Ocean), Cheju (or Jeju, East China Sea), and the islands around Japan have some common patterns, which are more or less developed depending on local circumstances and the effect of erosion and reshaping due to major landslides (Custodio 2007). Typically they are the result of a "hot spot" whose effusions pile up to form a basaltic shield volcano on the ocean floor, which at some point crops out and then subaerial volcanics substitute the submarine ones. In other cases, the shield volcano piles up on former sediments, even above sea level, as is the case of Mount Etna, in Sicily. Generally a calm period follows in which erosion and major landslides dissect and reshape the island. Volcanic activity may be reactivated, sometimes with well-defined ridges and rift zones, which may be the result of fracturing the ocean crust when the weight of the volcano is high enough. Then a second, smaller volcanic shield may develop, often with an initial phase of explosive volcanism (Hildenbrandt et al. 2005). Finally volcanism comes to an end—often the hot spot has moved to another position—except for sporadic episodes. However, these sporadic episodes can be important and cover large areas, as in the large historical eruptions in Lanzarote (Canary Islands), whose main volcanic shield is about 15.5 Ma (million years) old. In other cases, as in Easter Island, the structure is simpler since there is one dominating strato-volcano with a relatively homogeneous geology, at least in the surface, and there is no later rifting.

Volcanic islands may suffer important vertical movements, both drowning part of the island (as in the western Hawaii Islands) or elevating it up so that submarine volcanic formations (the case of Gomera and La Palma, Canary Islands) and even part of the ocean crust (Fuerteventura, Canary Islands; some of the Cape Vert Islands; Troodos Mountains in Cyprus) crop out.

From a hydrogeological point of view, young lava flows and their associated features, away from the emission centres, tend to be pervious to very pervious. Inland they may be unsaturated or hold some perched aquifers sustained by low permeability interlayerings. Near the coast, the water-table elevation of these young

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volcanic formations is often just slightly above local mean sea level and they contain a freshwater lens—sometimes a thin one—floating on intruding seawater, and separated by a variable thickness freshwater–saltwater mixing zone (Falkland and Custodio 1991; Custodio and Bruggeman 1987). In some cases, throughout parts of the coast, volcano-clastic sediments are found, generally heterogeneous and of low to moderate permeability. Depending on local circumstances, these sediments semiconfine young permeable volcanics below, as in Pearl Harbour and Honolulu, Oahu, Hawaii Islands (Hunt et al. 1988; Fujimura and Chang 1981; Voss and Wood 1994; Carracedo and Tilling 2003). They may also be a permeable feature when cover volcanics are unsaturated and the volcanics below are of low permeability, as happens in the Telde area, Gran Canaria, Canary Islands (Cabrera and Custodio 2004).

Volcanics affected by thermal metamorphism, dike injection, intense chemical weathering and intrusive bodies present low to very low permeability and form a volcanic "core", where the water table may be found at high elevation if recharge is high enough. Water–rock interaction may be important, especially if CO_2 from the depth is added. Dikes play an important role, both as relative low permeability intrusions and as water conducting features through the fissures associated. Numerous springs may appear, small ones if the recharge rate is small, or large ones in outcrops and thinnings of the cover, when recharge rate is high. All this is a common feature in many islands, although sometimes it is difficult to recognize when the vegetation cover is dense, slope debris accumulate and land relief is abrupt. All this can be seen in volcanic islands such as Oahu (Hawaii Islands), Tahiti-Nui (French Polynesia), Madeira and the seven Canary Islands, which have very different ages and variable stages of development. In other cases, even with high recharge, there are no inland springs, and the core does not crop out.

The hydrogeological knowledge of many of these volcanic islands is often incomplete since it derives mostly from springs at high elevation—whenever they exist—and wells and boreholes near the coast, where human activities concentrate. This in the case of Hawaii, Tahiti, Madeira, and the Azores in which groundwater in dike-impounded aquifers and basal aquifers has been distinguished, in limited areas of the islands. A more comprehensive point of view can be obtained considering only a main groundwater body in a quite heterogeneous medium. This is the approach developed for the Canary Islands (Custodio 2007; Custodio and Cabrera 2002) that explains what is observed in an extensive network of visitable, long water galleries and shaft wells, and numerous boreholes, at very different altitudes. This fact explains the importance of the Canary Islands to define volcanic island hydrogeological models and why they are used as a main reference in this report.

Groundwater recharge in volcanic islands is highly variable according to very diverse circumstances. Some are in arid and semi-arid environments; although the altitudinal effect on rainfall is important if elevation is high enough—as in the western Canary Islands—while others are in wet tropical areas and may record up to several meters/year of rainfall. Overland flow in recent volcanics is nil or low but can be high in older volcanics and in the outcropping core areas, as in Gran Canaria and Gomera (Canary Islands), where numerous high impounding dams have been constructed. In wet environments, annual recharge may be up to or higher than 50% of yearly precipitation (Falkland and Custodio 1991).

As will be explained in further sections, Easter Island is smaller than those mentioned above, is relatively young, and there is no clear indication whether a volcanic core exists or not. Hydrogeological information is mostly limited to the coastal area. In order to extend the knowledge to the whole island, in the absence of inland permanent springs and boreholes, some water samples from lava tube drippings and rainfall are used. Thus, this report offers some new knowledge applicable to this particular situation, which presents differences in comparison with other volcanic islands. This is a new contribution to the formulation of the conceptual hydrogeological model of these types of small, relatively high volcanic islands. A reference island is El Hierro (Canary Islands), in which the core has been unearthed, but with a coastal belt of highly pervious, young volcanic flows.

The report contributes knowledge about Easter Island and how to further it. Firstly, data will be presented in the Results section, followed by a discussion (see section Discussion). Results contain first comments necessary to understand data, and they include some preliminary elaboration, although the full elaboration is in the discussion section. The report ends with summary conclusions and contains some applied considerations. The main objectives are estimating recharge, characterizing groundwater flow and demonstrating that groundwater salinity in near-the-coast wells is due to mixing with seawater, in spite of the high inland recharge.

Background data on Easter Island

Easter Island is in the Pacific Ocean, at 27°09′30″S latitude and 109°24′14″W longitude (Fig. 1), and is part of the national territory of Chile, where it is known as Isla de Pascua (the Castilian name). The native Polynesian name is Rapa Nui. The surface area is 166 km^2. It is one of the most geographically isolated places in the world, 3,700 km away from the Chilean coast. Easter Island has about 5,500 inhabitants, 2,700 of which live in Hanga Roa, the capital.

The island has interesting archeological values, especially the large stone sculptures known as "Moais", the result of an enigmatic, disappeared civilization still to be fully explained by archeologists. The first inhabitants probably arrived around AD 1200 (Hunt and Lipo 2006). The cultural riches and the exotism of the island have made it a national and international tourist attraction since the 1990s. This has largely increased the number of visitors and thus has significantly increased the demand for freshwater.

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The island has a triangular shape and is dominated by Terevaka volcano, 507 metres above sea level (m asl), whose summit is toward the north of the island. It presents cliffs and steep slopes at the north and more gentle slopes to the south, east and westwards. Two other volcanoes close the triangle to the southeast (Poike, about 370 m asl) and the southwest (Rano Kau, about 324 m asl), but are not considered here.

The island has a warm-temperate, maritime climate, influenced by the Pacific high atmospheric pressure area. The 7–year average precipitation near the capital (Mataveri station) is 1,126 mm/year (Hajek and Espinoza 1987). April, May and June are the rainiest months (with monthly values above 100 mm), while during the rest of the year precipitation is lower but still significant. There is no rainfall network that can monitor spatial changes, but some measurements (Hajek and Espinoza 1987) show that rainfall is heavier in Vaitea (southern mid slope), intermediate in Sanatorio (western sector) and lower in Mataveri (near Hanga Roa).

In general, Easter Island temperatures are gentle, with small changes during the year due to the influence of the ocean. The average monthly temperature range is about 5°C, with minima in July–September (about 18°C) and maxima in January–March (about 23°C). The highest extreme temperature in the Austral summer months is 28° C and the lowest temperature is 14.6°C. Mean yearly soil temperatures will be given in the Discussion section.

Potential evapotranspiration is about 850–950 mm/year (Pincheira 2003). It is overwhelmed by the average annual precipitation falling on the island. There is either no clear soil humidity deficit during a typical year or it reduces to a short period. These factors point to an aquifer recharge rate of at least a few hundred mm/year over most of the island. Estimations will be presented later on.

It seems that the island was covered with trees when the first settlers arrived. It is said that they were responsible for its total deforestation and that ended their civilization. Currently soil is thin and poor, but exists, except on the more recent lava flows and volcanics. Vegetation is mostly of herbaceous type and grazed by cattle, but there are also some large eucalyptus tree plantations in Vaitea.

The surface drainage network is almost inexistent except for a few coastal creeks. Rainfall runoff is very low and most of the precipitation infiltrates the soil. The existence of surface water is limited to some shallow crater lakes. They are all closed basins except Rano Aroi, near Terevaka summit, which outflows through a small ravine that infiltrates downstream in about 400 m. This lagoon is not permanent since it periodically reduces to a peat bog.

Previous hydrogeological studies of Easter Island are very scarce and correspond to unpublished reports from consulting firms. The first study considering Easter Island hydrogeology was drafted by Hauser (1986), in which the author considers a possible water supply to the capital by means of a gallery network to drainwater from the permanent Rano Kau water lagoon. A more detailed hydrogeological study was that of Alamos y Peralta (1992), in which there is diverse hydrogeological information concerning water quality and aquifer hydraulic parameters, and presents a simple steady simulation groundwater flow model. Recently the Universidad Católica del Norte (UCN, Chile), with the help of the Geological Survey of Spain (IGME), has carried out new studies and samplings, partly explained in Pincheira (2003), which are presented in this report.

Geological framework of Easter Island

Easter Island is one of the volcanic edifices rising from the Pacific Ocean floor. It can be considered one of the manifestations of the large magmatic superswell emplaced between Australia and South America, south of the Equator (McNutt 1998). Its geology is dominated by the volcanic activity corresponding to three main edifices (Derruelle et al. 2002). From older to younger, they are the volcanoes Poike, Rano Kau and Terevaka (Fig. 1).

The Poike volcano, the oldest one, developed after two main effusive episodes, K/Ar-dated between 2.5 and 0.8 Ma (Clark and Dymond 1977). It is a strato-volcano formed by the piling up of many lava flows, mostly basalts and hawaiites. In the cliffs at the north of the volcano about 50 lava flows can be seen between 1 and 5 m thick each. Most of these flows are of the "aa" type, with scoria layers at the base and at the top, although there are also some "pahoe-hoe" flows intercalated.

The Rano Kau volcano is more or less contemporaneous to Poike, and presents a main caldera crater 1.5 km in diameter, which contains a lagoon about 6 m deep (Hauser 1986). Rano Kau is aged between 2.56 and 0.18 Ma. It is also formed by a piling of basaltic flows, grading from hawaiites to benmoreites. The lower part of Rano Kau is composed of relatively thin basaltic lava flows interbedded with pyroclastics (Baker et al. 1974).

Terevaka is the largest, highest, and more recent volcano, and it is the dominant feature of Easter Island. It is formed mainly by laminar flows of basalts, hawaiites and less frequent benmoreites. About 104 eruptive centres can be seen, forming craters, cones and domes. The oldest flows crop out in the north slope and correspond to aphanitic basalts. The absolute age for some lava flows is 0.36 Ma, although older flows, now covered by more recent ones, are possible (González-Ferrán 1987). Last volcanic activity is assumed to be 10,000–12,000 years old, and corresponds to the Hiva-Hiva lava, in Rohio area (González-Ferrán 1987). This volcano differs from Poike and Rano Kau in the fact that Terevaka does not present a main crater. The lava flows that build up this volcanic edifice are the result of many eruptions controlled by two main fracture systems, whose successive lava flows and pyroclastic cones formed the main body of the present island, and embody the older Poike and Rano Kau volcanoes that were former small, independent "islands". The geological survey carried out in the western coastal cliffs show that the structure of Terevaka volcano is a

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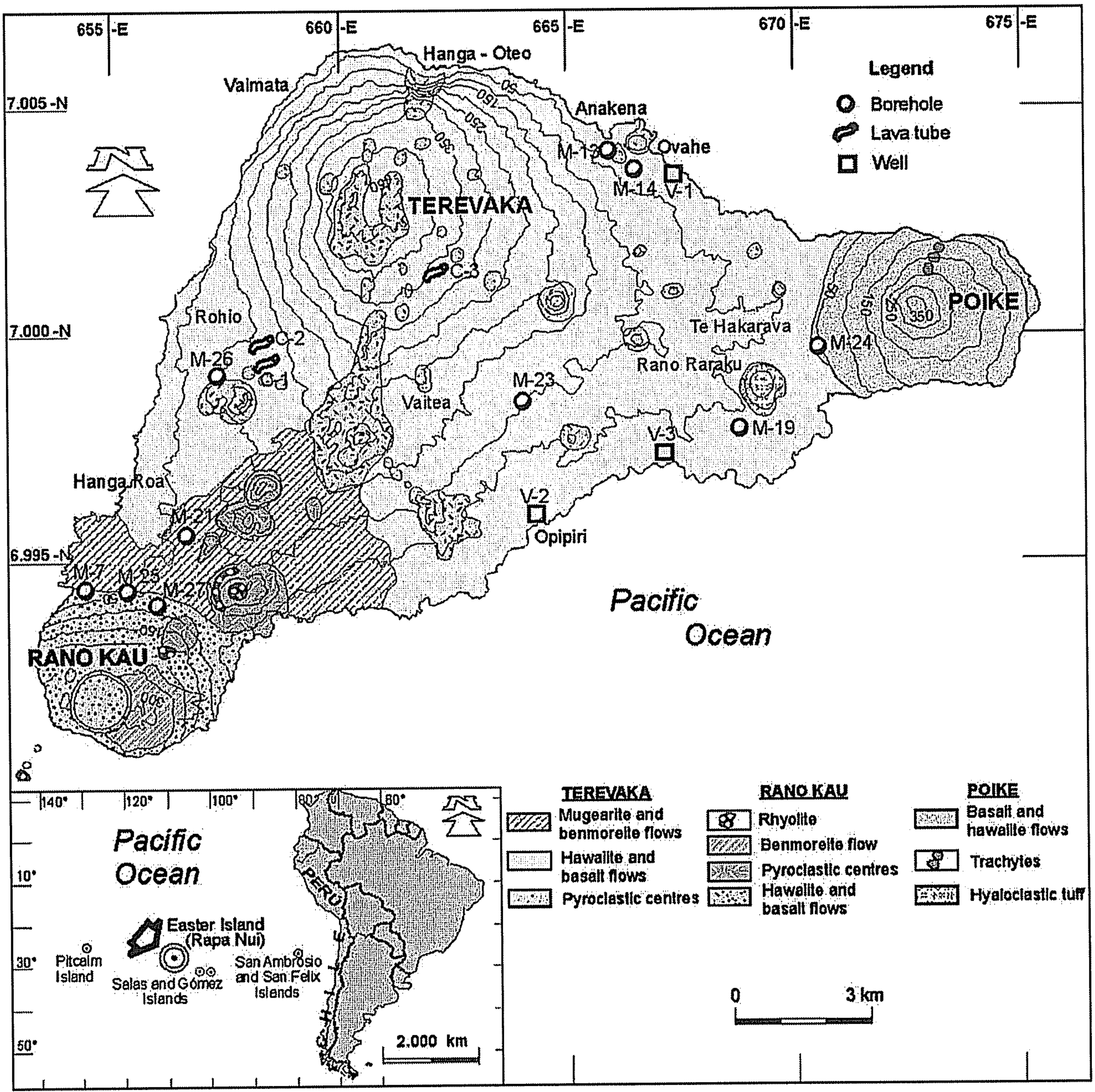

Fig. 1 Easter Island map showing the geology, topography, volcanoes, boreholes and sites mentioned in the text. Altitudes are in m asl

continuous piling of basaltic lava flows, 1–2 m thick. However, in the creeks of the Rohio area, a small 1-m thick palaeosoil level was found, with a lateral continuity of several hundred metres, although it does not seem to behave as a low permeability layer capable of supporting permanent, perched springs.

Groundwater flow in Easter Island

The available groundwater flow information consists of static levels measured by Alamos y Peralta (1992), which have to be complemented by the measurements carried out in the May 2002 partial survey. No significant groundwater level changes are observed comparing the two surveys. Most sampling points are tubed boreholes drilled in the 1960s, 17–102 m deep. There are also some shallow excavated wells near the shore. Both the boreholes and the wells only penetrate 0.5–2 m below the water table. This probably reflects local experience about the increasing groundwater salinity with depth. Figure 2 shows the water-table elevations relative to mean sea level, although the datum may not reflect the true mean local position of sea level.

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Taking into account that most of the geological structure of Easter Island is dominated by the Terevaka volcano materials, groundwater flow interpretation is done by considering the geological structure of this volcano. The different geological surveys consider that Terevaka volcano seems to be associated with two fissural eruptive centres, defined mainly by two fracture systems. They show up through the small eruptive centres and pyroclastic cones found along the indicated directions (Baker et al. 1974; González-Ferrán 1987). Then one may assume the presence of the feeding dikes of these eruptive centres, with a possible radial distribution from the volcano summit. This and the associated thermally altered rock may constitute a core area. However, in Terevaka volcano, and in the whole Easter Island, neither highly altered rocks nor dike clusters have been found, and this may be due to the poorly eroded recent lava flows and pyroclastics.

The radial distribution of feeding dikes may favour groundwater flow towards the periphery. Outside this central area, the piling up of lava flows seems to produce a high permeability apron at large scale. Most boreholes and wells are in the southern coastal area of Easter Island, and consequently there is no information on what happens in other areas. With the scarce available data, a water-table map cannot be drawn except in some areas near the coast. Horizontal water gradients are small in the coastal area, between 0.5 and 2‰ in recent volcanic materials.

Alamos y Peralta (1992) have evaluated pumping test data carried out when boreholes were drilled. They obtained transmissivity values between 20,000 and 40,000 m^2/day for these low penetration boreholes. These high transmissivity values, perhaps overestimated, correspond to the first saturated metres. They indicate permeabilities greater than 1,000 m/day for the young volcanic formations with scoria layers in unweathered lava flows. For the basalts filling the depression of Pearl Harbor (Oahu Island, Hawaii) transmissivity values up to 100,000–500,000 m^2/day are mentioned, corresponding to thicknesses of several tens of metres (Lau 1967; Gingerich and Voss 2005). Also very high values are mentioned around lacustrine areas of Central America (Krásný and Hecht 1998). In recent coastal lava flows of Lanzarote (Canary Islands), values exceeding 10,000 m^2/day have been found for only a few metres of penetration below the water table (Custodio 1973, 1978).

In the surface of Easter Island, numerous lava tubes have been found, up to several hundred metres long. Thus, it cannot be ignored that these types of volcanic features are present in the coastal saturated zone, making the medium highly heterogeneous.

The lack of springs and perched aquifers in relatively well recharged Easter Island points to the absence of shallow low permeability layers and formations, although recharge may flow out of sight through the recent volcanics near the surface. In the Rano Kau and Rano Aroi craters (near the summit of Terevaka volcano), and Poike and Rano Raraku volcanoes, there are lagoons that may contain water bodies some metres deep and placed several tens of metres above the island water table. The Rano Aroi lagoon, near the Terevaka volcano summit, outflows though a small creek. The flowing lagoon may correspond to the water table outcrop or to a perched aquifer. It can be assumed that the other mentioned lagoons are hydraulically perched above the inland water table, probably sustained by hydromorphic lacustrine formations of very low permeability. This is a common situation in rainy, vegetated areas such as the maars of Auverne, in the French Central Massif, and in the Eiffel area, Germany, although this does not happen in the young volcanic areas of the Canary Islands where organic matter deposits and clay-rich lacustrine sediments have not been formed due to more arid conditions. The possibility of local, highly altered, very low permeability volcanic rocks in Easter Island, perhaps through hydrothermal processes, has not been studied. In the largest of Easter Island lagoons, in Rano Kau volcano, whose cone forms a cliff over the sea, no external outflows are seen except for small seepages.

New surveys in Easter Island

When hydraulic data and boreholes are scarce and do not cover the study area, it is not possible to define groundwater functioning—chemical and environmental isotope analyses of rainwater, soil water, wells and boreholes, and small springs and seepages may contribute a fast, low-cost method to improve the hydrogeological conceptual model by incorporating information of areas without data and checking the hypothesis about the areas with data. This is the case of Easter Island, and a main contribution of this report.

The chemical and isotopic characterization of Easter Island groundwater and surface water is the result of data obtained in two field samplings carried out in May 2002 and October 2003. This means field samples from boreholes, wells, lagoons and lava tubes. Additionally, monthly rainfall samples were collected in the period from June 2002 to February 2003. Sampling included in situ measurement of groundwater level, electrical conductivity (EC), pH, temperature and alkalinity, in surface and groundwater samples, using conventional measuring devices. Samples were filtered (0.45 μm) in the field after sampling, and an aliquot for cation analysis was preserved with 1% HNO_3 acid. Chemical analyses follow standard procedures.

A total of 52 rainfall, lagoon, lava tube and groundwater samples were analysed for major ions (Tables 1, 2 and 3), in the Geological Survey of Spain (Instituto Geológico y Minero de España, IGME) certified laboratory in Tres Cantos, Madrid. Many samples have electrical conductivities lower than 200 μS/cm.

A total of 25 water samples for ^{18}O and ^{2}H analyses and a total of 19 water samples for ^{3}H analysis were obtained. Samples for ^{13}C in dissolved inorganic carbon,

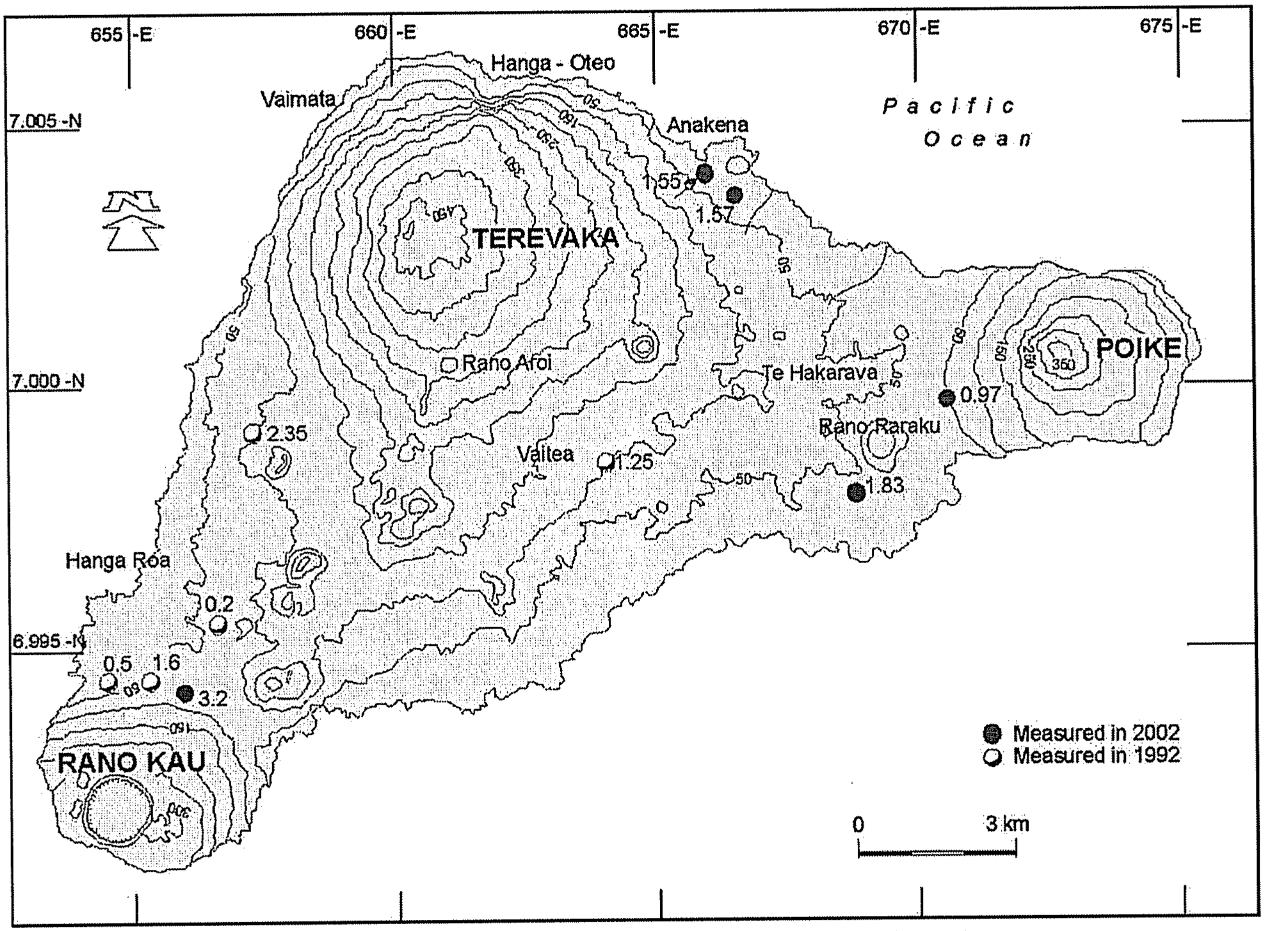

Fig. 2 Groundwater head elevation in open wells and deep boreholes. Altitudes and heads are in m asl

and ^{34}S and ^{18}O of dissolved sulphate in water were obtained from precipitates prepared in the field. These results have to be added to the δ^{18}O, δ^{2}H and ^{3}H analyses of precipitation from Easter Island obtained from the GNIP/ISOHIS data base (Global Network of Isotopes in Precipitation/Isotope Hydrology Information System) maintained by the International Atomic Energy Agency (IAEA) for the world-wide atmospheric water isotopic network. These data correspond to monthly δ^{18}O and δ^{2}H concentration in precipitation collected between 1964 and 2000 in Mataveri station, near Hanga Roa, at an elevation of 41 m asl.

^{18}O, ^{2}H and ^{3}H analyses were carried out in the CEDEX laboratory in Madrid. ^{13}C, ^{34}S and ^{18}O (dissolved sulphate) analyses were carried out by the Laboratory Services of the University of Barcelona. Reported values refer to international standards: VSMOW (Vienna Standard Mean Ocean Water) for ^{18}O and ^{2}H, VPDB for ^{13}C and CDT for ^{34}S. References to these standards have been omitted in the text. Tritium has been measured in a scintillation counter after electrolytic enrichment. Accuracy is ±0.1–0.2 TU and this has been omitted from reported data.

Chemical results

Analyses from the 20 rainfall samples from Hanga Roa and Vaitea (Table 1) show that the pH is about neutral; some data point to the incorporation of some local atmospheric soil dust. The average chloride content clusters around 7.6 mg/L for Hanga Roa and 6.3 mg/L for Vaitea, which is further inland. The range of Cl for dust unaffected samples is relatively small for rainfall samples and thus the average values can be used as an approximation of the long-term average value. The Na and Mg content corresponds to diluted seawater (airborne salts) and SO_4 is somewhat higher. The ratio rCl/rBr (r=meq/L) corresponds to measurements of Cl and Br in the same aliquot, thus avoiding dilution errors. Disregarding extreme values, the ratio clusters around 775 for Hanga Roa and 825 for Vaitea, slightly above the marine value (655±4), as it is also the case for the dry areas of the Canary Islands (Custodio and Herrera 2000).

Analytical results from the lava tube drippings and the lagoons are in Table 2. The roof of the sampled lava tubes is 3–5 m below land surface so they represent local recharge waters in transit through the unsaturated zone.

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Table 1 Major element composition and Br^- of Easter Island rainfall

Sample (20°C)	Sampling date	EC	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	SiO_2	Br	rCl/rBr
Hanga Roa	30-Jun-02	34	7	5.1	<1	1	2	8.3	2	4	<0.5	0.1	0.023	798
Hanga Roa	31-Jul-02	25	6.3	3.8	<1	1	1	5.6	0.9	3	-	0.1	0.016	798
Hanga Roa	31-Aug-02	60	7.2	9.3	<1	3	1	14.3	3	10	-	0	0.050	646
Hanga Roa	30-Sep-02	38	7.6	5.7	<1	2	1	7.8	8	9	-	0	0.016	1071
Hanga Roa	31-Oct-02	25	7.5	2.5	<1	2	1	3.7	7	2	-	0	0.006	1331
Hanga Roa	30-Nov-02	31	7.4	3.0	<1	4	1	3.0	3	13	1	0.1	0.065	102
Hanga Roa	30-Dec-02	178	6.9	9.3	1.3	28	1	11.9	4	81	1	1.8	0.035	839
Hanga Roa	30-Jan-03	155	7.2	6.6	<1	29	1	8.0	2	84	1	0.8	0.023	789
Hanga Roa	28-Feb-03	34	7.4	4.5	<1	5	1	5.2	3	14	<0.5	0.2	0.020	592
Hanga Roa	1-May-03	-	-	5	<1	2	1	8	3	5	-	0.9	-	-
Vaitea	30-Jun-02	23	7.3	4.0	<1	1	1	5.7	1	1	<0.5	0.1	0.018	699
Vaitea	31-Jul-02	37	6.9	6.1	<1	1	1	9.1	1.4	2	-	0.1	0.028	798
Vaitea	30-Sep-02	38	7.2	4.1	<1	3	1	5.4	2	12	-	0	0.014	852
Vaitea	31-Oct-02	36	7.6	4.2	<1	3	1	4.8	3	9	-	0	0.008	1325
Vaitea	30-Nov-02	22	7.4	2.7	<1	3	1	2.5	4	6	1	0.4	0.007	821
Vaitea	30-Dec-02	64	7.3	5.8	<1	8	1	7.6	3	21	<0.5	0.6	-	-
Vaitea	30-Jan-03	66	7.1	4.5	<1	9	1	5.6	3	25	<0.5	1.4	0.012	1062
Vaitea	28-Feb-03	49	7.5	6.3	<1	5	1	8.6	3	11	<0.5	0.4	0.249	78
Vaitea	1-May-03	-	-	3	<1	5	2	4	2	27	-	0.6	-	-
Vaitea	1-Jun-03	-	-	8	<1	7	2	14	3	24	-	0.1	-	-

Concentrations in mg/L. The prefix 'r' means that the ratio is from concentrations in meq/L. *EC* electrical conductivity at 20°C in μS/cm

Lagoon waters are slightly acid and those from the lava tubes are neutral. Silica content is low (4–9 mg/L), which indicates a small water–rock interaction, as is also shown by the low bicarbonate content (3–15 mg/L). Chloride content is about 15 mg/L in most cases. Higher values at Rano Kau lagoon are due to evaporation. In flowing Rano Aroi lagoon the low values dominate, while silica and bicarbonate content is higher, which may reflect a greater soil–water–rock interaction. In these waters, there is a slight excess of Na over Cl (rNa/rCl=1.0–1.2) with respect to seawater (rNa/rCl=0.83), except for Rano Kau lagoon, which is close to the marine water ratio. Furthermore, there is an excess of Mg over Cl (rMg/rCl=0.4–0.8), and again Rano Kau lagoon is closer to the seawater ratio, and it has also an excess of sulphate over chloride (0.15–0.34). The ratio rCl/rBr from the lava tubes tend to be lower than the value for seawater, although higher values are found for the lagoons and the Rano Aroi lava tube.

The analytical results for boreholes and wells are in Table 3. They show the soil–water–rock interaction through the relatively high silica content (50–60 mg/L), moderate bicarbonate content (70–110 mg/L) and slightly basic pH (7.2–7.5). There is also some phosphate (0.1–0.5 mg/L), and nitrate (3–8 mg/L). Some samples in inhabited areas may show a high nitrate content that may be explained as due to local anthropogenic contamination. Ammonia is normally below 0.05 mg/L although some samples may present measurable quantities that may reflect the mentioned local contamination. The rNa/rCl ratio (0.8–1.0) indicates some excess of Na over Cl with respect to seawater. Relative magnesium content (rMg/rCl=0.2–0.3) is close to seawater or somewhat in excess, and the same happens for sulphate (rSO_4/rCl=0.08–0.13). The rCl/rBr ratio tends to coincide with that of seawater (655±4) or is somewhat above it.

All borehole and well waters are of the sodium chloride type (Fig. 3) and only the Vaitea borehole (M-23) has low salinity, but higher than that of the lava tubes and the lagoons. The diagrams show the conspicuous difference between lava tube water (and M-23 borehole) and water from the wells and boreholes.

Isotopic results

The plot of $\delta^{18}O$ vs. δ^2H for rainfall (Fig. 4) shows that these data follow the world mean meteoric water line (‰) defined by Craig (1961), with some deviations, and a trend towards a lower deuterium excess ($d=\delta^2H-8\delta^{18}O$‰) for isotopically heavy samples. This also happens in other small tropical islands (Yurtsever and Gat 1981). It is the result of partial condensation of locally generated marine vapour in areas of fast evaporation (Dansgaard 1964) before attaining the isotopic equilibrium between liquid and gas phases.

Borehole and well water data (Table 4) range from −2.31 to −3.16‰ for $\delta^{18}O$ and −9.5 to −20.1‰ for δ^2H. They are also close to the world mean meteoric water line (Fig. 4). Deuterium excess is about 10‰ for recharge water but may be as low as 5‰, an expectable feature in the oceanic environment. Differences in the results of the two field surveys may be the result of changes in the mixing pattern inside the boreholes or wells due to pumping.

Strontium isotopes have been measured to ascertain the relative influence of water–rock interaction and seawater admixture, since their $^{87}Sr/^{86}Sr$ ratio is quite different. Results are in Table 4.

Some borehole samples have been analysed for dissolved sulphate isotopes ($\delta^{34}S$ and $\delta^{18}O$). It has not been possible to carry out analyses of the lava tubes water due to the low sulphate concentration. The $\delta^{34}S$ from Easter Island groundwater is very homogeneous (Table 4) and close to the $\delta^{34}S$ of marine water sulphate (+21‰), except for borehole M-23, with a $\delta^{34}S$ of +18.9‰. $\delta^{18}O$

Table 2 Major element composition and ionic ratios for lava tube drippings and lagoons

Sample	Site	Sampling date	N(UTM)	E(UTM)	T(°C)	EC	pH	Na	K	Ca	Mg	NH_4	Cl	SO_4	HCO_3	CO_3	NO_3	PO_4	SiO_2	rNa/rCl	rMg/rCl	rSO_4/rCl	rCl/Br
C-1	Rohio	May 2002	7000268	658440	19.7	90	7.1	11	<1	2	3	<0.05	16	5	17	0	<0.5	<0.05	9.9	1.02	0.55	0.23	535
C-2	Rohio	May 2002	7000172	658212	18.4	83	7.3	11	<1	1	2	<0.05	14	5	14	0	<0.5	<0.05	7.3	1.26	0.42	0.26	563
C-3	Rano-Aroi	May 2002	7001165	661595	-	-	-	11	<1	3	4	<0.05	15	4	29	0	<0.5	<0.05	20.1	1.09	0.78	0.20	396
L-1	Rano-Aroi	May 2002	7000400	661350	18.6	88	5.5	10	<1	1	4	<0.05	15	7	15	0	<0.5	<0.05	4.8	1.06	0.78	0.34	922
L-2	Rano-Kau	May 2002	6992000	654500	23.9	140	4.6	17	<1	2	4	0.45	34	8	3	0	<0.5	<0.05	3.9	0.76	0.34	0.17	646
C-3	Rano-Aroi	Oct 2003	7001165	661595	17.5		6.5	20	4	10	9	0.2	45	13.9	50	0	4	<0.05	22.3	0.69	0.59	0.23	710
C-2	Rohio	Oct 2003	7000172	658212	17.4		7.4	10	<1	1	3	<0.05	16	3.1	16	0	<0.5	<0.05	9.2	0.96	0.55	0.14	422
C-1	Rohio	Oct 2003	7000268	658440	16.9	122	7.4	10	<1	1	3	<0.05	16	3.5	16	0	<0.5	<0.05	8.2	0.96	0.55	0.16	406

Concentrations in mg/L. The prefix 'r' means that the ratios are from concentrations in meq/L. *EC* electrical conductivity at 20°C in μS/cm; *C* lava tube dripping; *L* lagoon

of current marine sulphate is +9.6‰. The $\delta^{18}O$ of sulphate from borehole water (Table 4) are slightly above the marine value, with an exception.

The isotopic composition of dissolved inorganic carbon (DIC) in borehole water ranges from −5.5 to −10.0 ‰ for $\delta^{13}C$. Two samples were recovered from the lava tubes. They show very different $\delta^{13}C$ values. In Rano Aroi (C-3), lava tube the sample does not correspond to dripping water (too scarce) but to water pooled on the lava tube floor, with a $\delta^{13}C$ of −20.1 to −22.0‰. In the Rohio lava tubes, two samples were recovered from the roof dripping with $\delta^{13}C$ of −8.6 ‰ (C-1) and −14.3‰ (C-2). In the area of Rano Aroi, there are plenty of eucalyptus trees, which are plants following the Calvin (C-3) cycle producing soil CO_2 with $\delta^{13}C$ about −24‰. In the area of Rohio, soil is poor and vegetation is herbaceous and scarce since they are relatively unweathered, recent lava flows.

The tritium content of Easter Island groundwater is presented in Table 4 and refers to years 2002 and 2003. Groundwater with the highest tritium contents corresponds to the lava tube waters, with values above 1.2 TU (tritium units) and a maximum of 1.8 TU in sample C-3. The lava tube samples correspond to rainwater flowing through a few metres of unsaturated zone before dripping into the lava tubes. Samples from the eastern part of the island boreholes have a greater tritium concentration while samples from the western part have a lower content.

Discussion

Recharge

Using field measured groundwater temperatures (Tables 2 and 3), it is possible to draw some spatial distribution of environmental temperature after correcting for geothermal gradient in deep boreholes. Although this local thermal gradient is unknown, a 2–3°C per 100 m depth is assumed, which is close to the continental average and agrees with the thermal gradient found in the Canary Islands away from areas with recent volcanic episodes. Results are summarized in Table 5 and correspond to the measured groundwater temperature less the vertical thermal gradient times the sample depth. Temperatures of 21–22°C can be expected near the coast, 18°C at the slopes and 17°C near the top.

To get an initial understanding of groundwater recharge, the formulae of Coutagne and Turc (Custodio and Llamas 1976) are used to derive an estimation of actual yearly average evapotranspiration (AET), using probable values of average yearly precipitation (P), which is only measured at Mataveri, but according to what has been said before, it is assumed to be higher inlandwards. A value of 1,100 mm/year may represent the average value at the coastal area and 1,500 mm/year at the highlands.

The Coutagne formula is AET=$P-\chi P^2$, for values in m/year. $1/\chi = 0.8 + 0.14t$, for t (average temperature) in °C, if $1/P$ is between 8χ and 2χ.

Table 3 Major element composition and ionic ratios of groundwater in Easter Island

Sample	Site	Sampling date	N (UTM)	E (UTM)	T (°C)	EC	pH	Na	K	Ca	Mg	NH_4	Cl	SO_4	HCO_3	NO_3	PO_4	Sr	SiO_2	rNa/ rCl	rMg/ rCl	rSO_4/ rCl	rCl/ Br
M-7	Mataveri	May 2002	6994337	654761	24.1	1271	7.3	184	11	25	29	<0.05	320	34	86	6	0.09	-	56.2	0.89	0.27	0.08	636
M-13	Anakena	May 2002	7003926	666253	22.1	2800	7.5	426	21	40	68	<0.05	856	127	77	3	0.38	-	64.8	0.77	0.23	0.11	737
M-14	Anakena	May 2002	7003740	666891	22	4100	7.4	741	26	40	50	<0.05	1090	186	79	9	0.25	-	51.8	1.05	0.13	0.13	645
M-19	Rano-Raraku	May 2002	6997959	669105	22.6	3520	7.3	525	20	28	69	<0.05	910	141	67	4	0.29	-	54.2	0.89	0.22	0.11	703
M-21	Hanga-Roa	May 2002	6995525	656912	23	2510	7.2	349	18	38	65	<0.05	570	99	210	3	0.55	-	70.8	0.95	0.33	0.13	629
M-24	Te Hakarava	May 2002	6999834	670774	26	1454	7.5	234	11	17	22	<0.05	362	36	84	7	0.12	-	51.2	1.00	0.18	0.07	685
M-23	Vaitea	May 2002	6998567	664324	21.6	246	7.7	31	2	5	8	<0.05	42	7	59	3	0.19	-	53.8	1.14	0.56	0.12	547
M-25	Mataveri	May 2002	6994360	655486	23.7	899	7.6	118	8	16	20	<0.05	198	19	86	7	0.13	-	57	0.92	0.30	0.07	624
M-26	Sanatorio	May 2002	6997758	657391	22	1640	7.7	251	11	13	30	<0.05	394	41	96	2	0.33	-	56	0.98	0.22	0.08	742
M-27	Mataveri	May 2002	6994207	656240	23.8	692	7.5	98	6	12	17	<0.05	138	25	20	83	0.12	-	59.6	1.09	0.36	0.13	595
V-1	Ovahe	May 2002	7003836	667449	21.2	7100	7.6	1237	47	64	98	<0.05	1950	298	79	4	0.28	-	52	0.98	0.15	0.11	626
V-2	Opipiri	May 2002	6995864	664642	-	-	-	364	16	26	47	<0.05	580	97	103	7	0.55	-	52.8	0.97	0.24	0.12	582
V-3	Hanga Te Tenga	May 2002	6997163	667163	-	-	-	832	28	52	84	<0.05	1295	262	111	6	0.37	-	48.4	0.99	0.19	0.15	661
M-7	Mataveri	Oct 2003	6994337	654761	23.8	1215	7.3	129	10	25	23	<0.05	268	26	74	7	0.11	0.226	58.2	0.74	0.25	0.07	604
M-13	Anakena	Oct 2003	7003926	666253	22	2500	7.4	446	22	35	56	<0.05	836	103	56	3	0.29	-	63.6	0.82	0.20	0.09	645
M-14	Anakena	Oct 2003	7003740	666891	22.1	3500	7.6	512	28	65	76	<0.05	1080	155	42	4	0.27	-	48.6	0.73	0.21	0.11	543
M-21	Hanga-Roa	Oct 2003	6995525	656912	23	-	7.2	217	14	39	56	<0.05	484	44	162	4	0.57	-	68.4	0.69	0.34	0.07	706
M-23	Vaitea	Oct 2003	6998567	664324	21.5	252	7.6	19	2	10	6	<0.05	34	4	50	5	0.29	0.058	49.4	0.86	0.52	0.09	587
M-24	Te Hakarava	Oct 2003	6999825	670785	25.9	2170	7.4	249	14	52	50	<0.05	592	60	52	7	0.11	0.162	47.2	0.65	0.25	0.07	706
M-25	Mataveri	Oct 2003	6994360	655486	23.8	803	7.7	88	7	18	18	<0.05	188	15	63	7	0.13	0.11	58	0.72	0.28	0.06	638
M-26	Sanatorio	Oct 2003	6997758	657391	21.6	1373	7.8	133	11	40	47	<0.05	392	33	52	3	0.35	0.158	55.6	0.52	0.35	0.06	665
M-27	Mataveri	Oct 2003	6994207	656240	24		7.6	62	6	17	15	<0.05	142	12	48	8	0.17	0.097	59.4	0.67	0.31	0.06	634
M-28	Mataveri	Oct 2003	6994307	655886	22.2	647	7.6	86	6	13	12	<0.05	145	12	66	8	0.19	-	56.8	0.91	0.24	0.06	635
M-19	Rano-Raraku	Oct 2003	6997959	669105	22.5	-	7.2	426	22	30	30	<0.05	790	104	90	5	0.26		56.4	0.83	0.11	0.10	576

Concentrations in mg/L. The prefix ‘r’ means that the ratios are from concentrations in meq/L. *EC* electrical conductivity at 20°C in µS/cm

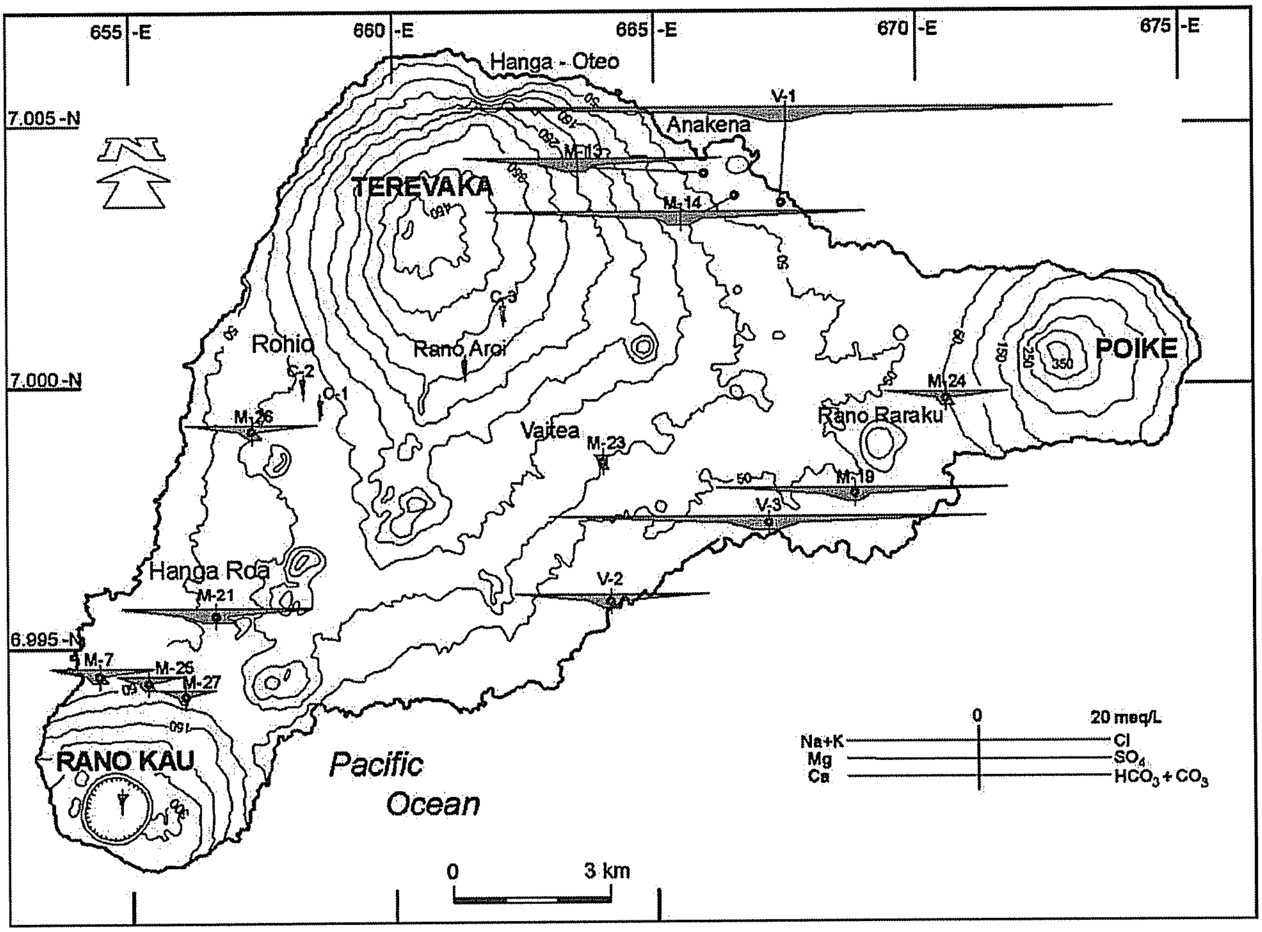

Fig. 3 Modified Stiff diagrams of Easter Island groundwaters. Altitudes are in m asl

The Turc formula is $AET = P\left(0.9 + P^2/L^2\right)^{-1/2}$ for values in mm/year. $L = 300 + 25t + 0.05t^2$, t in °C.

Results for AET are 680–775 mm/year for the coastal area and 630–790 mm/year for high elevation areas. These values are somewhat less than the 850–950 mm/year mentioned in the background data on Easter Island. Taking into account that surface runoff in the island is very small, long-term aquifer recharge can be estimated as P–AET, P being the mean yearly rainfall. This results in a recharge estimation of 325–420 mm/year near coastal areas and up to 720–870 mm/year in the highlands. These values have to be considered with great caution, and probably are overestimated to some extent. High recharge values are also mentioned for other islands with similar climate, as summarized in Falkland and Custodio (1991). Higher values, up to 800–1,400 mm/year, are mentioned for Madeira (van der Weijden and Pacheco 2003), and close to the mentioned values for Pico (Azores) at intermediate altitudes (Cruz and Silva 2001). Values can be much higher for wet tropical islands such as Martinique (Mouret 1979), between the Caribbean sea and western Atlantic Ocean, and Rêunion (Louvat and Allègre 1997) i the western Indian Ocean.

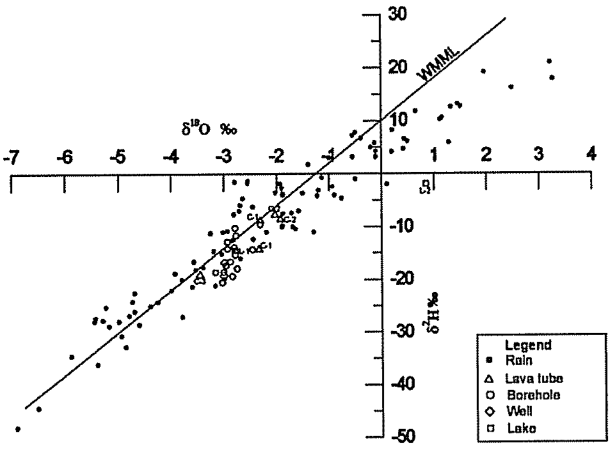

Fig. 4 Water isotopic composition of precipitation and groundwater from Easter Island. *WMML* world mean meteoric water line: $\delta^2H = 8\delta^{18}O + 10‰$

The southern slope of Easter Island can be approximated by a circular sector with the apex in Terevaka summit and the boundary along the coast between Rano Kau and Poike volcanoes, at an average distance of L=9 km. If recharge is assumed to vary linearly with altitude, from R_c=350 mm/

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Table 4 Isotopic composition of waters and solutes (in ‰ respect to the standard) and $^{87}Sr/^{86}Sr$ ratio of solutes of Easter Island

Sample	Description	Sampling date	$\delta^{18}O$(‰) SMOW	δD(‰) SMOW	^3H (TU)	d (‰)	$\delta^{13}C$ (‰) PDB	$\delta^{34}S(SO_4)$ (‰) CDT	$\delta^{18}O(SO_4)$ (‰) SMOW	$^{87}Sr/^{86}Sr$
M-7	Borehole	May 2002	-	-	0.69	-	−10.05(−12.73)			
M-21	Borehole	May 2002	-	-	0.70	-	−6.36			
M-24	Borehole	May 2002	−2.75	−17.70	1.07	4.3	−7.44			
M-23	Borehole	May 2002	−3.16	−18.40	1.07	6.9	−7.86			
M-25	Borehole	May 2002	−2.85	−19.00	0.72	3.8	−8.39			
M-26	Borehole	May 2002	−3.00	−18.80	0.77	5.2	−6.31			
M-27	Borehole	May 2002	−2.97	−17.00	0.61	6.8	−7.93			
M-13	Borehole	May 2002	−2.77	−11.50	0.86	10.7	−4.76			
M-19	Borehole	May 2002	−2.81	−13.80	1.09	8.7	−5.76			
C-1	Lava tube	May 2002	−2.31	−8.80	1.24	9.7	−8.61			
C-2	Lava tube	May 2002	−1.92	−8.50	1.77	6.9	(−14.29)			
C-3	Lava tube	May 2002	−3.45	−18.90	1.21	8.7	(−21.98)			
L-1	Lake	May 2002	−2.79	−14.30		8.0	-			
L-2	Lake	May 2002	0.85	−2.00	0.95	-8.8	-			
V-1	Well	May 2002	−3.00	−18.30		5.7	-			
V-3	Well	May 2002	−2.98	−16.70	1.00	7.1	-			
M-26	Borehole	October 2003	−3.03	−20.10	0.54	4.2	−6.7	20.55	12.12	0.707104
M-23	Borehole	October 2003	−2.79	−10.20	0.87	12.1	−7.21	18.9	10.18	0.704332
M-7	Borehole	October 2003	−2.88	−16.40	0.53	6.6	−11.42	20.68	18.73	0.706237
M-24	Borehole	October 2003	-	-	-		−9.35	20.89	13.34	0.707137
M-27	Borehole	October 2003	−2.79	−15.10	0.29	7.2	−8.65	20.27	9.85	0.705571
M-19	Borehole	October 2003	−2.46	−14.10	-	5.6	−7.09	20.52	11.6	
M-25	Borehole	October 2003	−2.31	−9.50	-	9.0	−9.46	20.87	11.79	0.705857
M-14	Borehole	October 2003	−2.93	−12.80	-	10.7	−8.38	20.28	11.22	
M-13	Borehole	October 2003	-	−12.00	-		−6.98	20.6	12.01	
M-21	Borehole	October 2003	−2.93	−14.00	-	9.5	−6.97	20.2	12.39	
C-1	Lava tube	October 2003	−2.34	−14.10	1.06	4.6	-			0.705067
C-2	Lava tube	October 2003	−2.03	−7.70	-	8.6	-			
C-3	Lava tube	October 2003	-	-	-	7.0	−20.12			

d excess deuterium = $8\delta^{18}O–\delta^2H$ (in ‰). *TU* tritium units ($10^{-18}\ {}^3H/{}^1H$). Tritium data ±0.1–0.2 TU

year at the coast to R_o=800 mm/year at the apex, and there is no intermediate groundwater discharge, total groundwater flow per unit (q), for the total flow depth, at distance r from the apex, can be easily calculated as:

$$q = \frac{1}{r}\int_0^r \left(R_e + \frac{R_0 - R_c}{L}r'\right)r'dr'$$

$$= R_c\frac{r}{2} + \frac{R_0 - R_c}{L}\frac{r^2}{3}$$

in which r' is an intermediate position between the apex and r.

$q=T\times i$ in which T = aquifer transmissivity and i = water table slope in r. Then $T = \frac{1}{i}\left(R_c\frac{r}{2} + \frac{R_0-R_c}{L}\frac{r^2}{3}\right)$

The application for Vaitea (borehole M-3), where i≈0.5‰ and r=5.5 km, yields T≈8,000 m^2/day. This value is inferior, although comparable, to the result from pumping tests.

From the chloride balance in the soil, the value of recharge can be estimated for steady state. This is a well-known procedure (see Simmers 1997; Custodio et al. 1997) under favourable conditions and it is a source of knowledge when other data are not available. If Cl_P is average chloride in rainfall (P) and R is average recharge as estimated above, the expectable chloride content in recharge water (Cl_R), assuming that overland runoff is small, is:

$$Cl_R = Cl_P \cdot P/R$$

Cl_R strictly corresponds to unsaturated zone water salinity below plants' root depth, but if recharge is high enough, this

Table 5 Estimation of surface temperature in Easter Island from temperature data of water in boreholes: $S \approx W - Z \cdot gradT$; gradT = vertical temperature gradient = 0.02 to 0.03°C/m

Site	Z Average depth (m)	W Water temperature °C	S Estimated soil temperature °C
Mataveri (N slope of Rano Kau). W Coast	50	23.8	22.3
Hanga Roa (W Coast)	70	23.0	21.0
Sanatorio-Rohio (W Coast)	100	21.8	18.8
Anakena (N Coast)	30	22.0	21.0
Southern coast	Small to 50	21.2–21.6	21.0
Poike west slope	50	26.0	24.5
Vaitea (south slope, inland)	100	21.5	18.5
Lava tubes near Rohio (W sector)	0	18.0	18.0
Rano Aroi lava tube (summit)	0	17.0	17.0

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value is maintained through the whole unsaturated zone depth and is reflected in the upper part of the groundwater body.

For Cl_P=7.6 mg/L at the coastal area and 6.0 mg/L at high elevation, and P=1,100 and 1,500 mm/year, and R=350 and 800 mm/year at the coast and at high elevation, respectively, it results in Cl_R=24 mg/L and 11 mg/L. The values at high elevation approach what is found in the lava tubes and the flowing Rano Aroi lagoon. They are about half of what is found in Vaitea (M-23), which may have some very slight marine contamination. This provides a crude although acceptable estimation of recharge rate in the island.

Groundwater salinity

There is an added salinity effect in boreholes and wells. Since halite sources are neither present in the island nor have they been detected in the rCl/rBr ratios (a high value must be found), the sea is the most probable source of well-water salinity, as destailed in the following.

The high recharge combined with the high transmissivity at the coastal area and the probable large permeable thickness points to a freshwater lens floating on intruding seawater in the aquifer, a common situation in many oceanic islands. If a sharp interface between fresh and saltwater is assumed and horizontal flow dominates, the Badon Ghyben-Herzberg principle can be applied (Custodio and Llamas 1976; Custodio and Bruggeman 1987). For each metre of water-table elevation above (true) mean sea level, there are 40 m of freshwater below. This result changes when vertical groundwater flow is present (Isuza and Gingerich 1998, 2003; Custodio and Bruggeman 1987), which is the case near the shore, where freshwater discharges into the sea.

In the case of the Vaitea borehole (M-23), the least affected by salinity increase, about 2.5 km from the shore, the water-table elevation is 1.25 m, assuming that the datum is the true average sea level. There, the freshwater–saltwater (sharp) interface is expected to be at about 50 m below sea level. Near Hanga Roa, the theoretical freshwater lens may be reduced to about 10 m thick, although it may be thicker in other less permeable areas, even places not far away from the sea. However, a sharp freshwater–saline-water interface is not expected due to extensive hydrodynamic dispersion produced by tidal fluctuations (0.2–0.3 m in some boreholes, according to Alamos y Peralta 1992), seasonal water-table oscillations, the effect of exploitation and the highly heterogeneous character of the aquifer. This is the experience in other islands, as in Pico, Azores (Cruz and Silva 2000, 2001), in the recent coastal volcanic areas of the Canary Islands (Hierro, Lanzarote), and in some Japanese small volcanic islands, and also in Hawaii (Izuka and Gingerich 1998, 2003).

The transmissivity values calculated earlier refer to the active freshwater flow thickness, which is less than the theoretical freshwater lens thickness. The value of 8,000 m^2/day means a permeability higher than 160 m/day, which is expected for this type of volcanics with unweathered scoria and breccia layers, and lava tubes. Pumping tests probably affect a thickness which may include part of the saline body, and thus transmissivity values may appear higher. There is no clear relationship between water–table elevation and salinity, and distance to the shore and salinity, although the trend is to find higher salinity the closer to the shore.

Hydrogeochemical characteristics

Sodium chloride type waters dominate, indicating a marine influence, which may be direct through the ground, or airborne, through marine aerosol, or by sea spray near the shore. No chloride contribution from the basalts can be expected and saline layers seem highly improbable, even considering submarine volcanic formations at depth. Water–rock interaction adds Na and some Mg.

Figure 5 shows the rCl/rBr, rNa/rCl, rMg/rCl and rSO_4/rCl ratios vs. chloride for rainwater, lagoon waters, lava tube drippings, wells and boreholes. Chemical values are in mg/L and ionic ratios in meq/L (indicated by placing 'r' before the chemical symbol) to make the comparison easier. Rainwater plots in a dispersed manner due to natural variability, the effect of incorporating variable quantities of dust and the chemical uncertainty associated with the small concentrations. The most important results are:

- Starting from rCl/rBr values (Fig. 5a) less than that of seawater, which represents recharge water, the ratio tends progressively to the marine value as Cl content in groundwater increases. Evolution follows a mixing line between recharge water and seawater. The lower-than-seawater ratio for recharge water agrees with what is normally found as background values in other aquifers (Davis et al. 1998; Custodio and Herrera 2000).
- Recharge waters have an excess of Na over Cl (Fig. 5b) explained by what can be expected after water–rock interaction. As Cl content in groundwater increases there is a fast evolution towards the marine value, following possible mixing lines that start at the local rNa/rCl values. Although there is a permanent Na excess (not shown), it is not reflected in a systematic equivalent bicarbonate increase. Thus, exchange with Mg sorbed in the solid may be expected.
- Recharge waters also have a clear excess of Mg over Cl (Fig. 5c), which is explained by what can be expected after water–rock interaction. There is a fast evolution towards the marine value as Cl content in groundwater increases, partly due to exchange with Na.
- Recharge water has a small excess of SO_4 over Cl (Fig. 5d), which can be expected from background local rain characteristics. There is an evolution towards typical marine values as Cl in groundwater increases.

All this points to seawater as the cause of well water salinization. Ca and HCO_3 content evolve similarly, which can be explained by $CaCO_3$ dissolution by CO_2 (not shown here), and the rNa/rCl ratio tends towards the marine value as HCO_3 increases. This means that soil CO_2 contributes only a fraction of the total dissolved inorganic carbon in saline groundwater, and that some source of calcium carbonate may be present such as remnants of biological marine activity (shells), secondary volcanic minerals or dust contribution. Changes in Na excess and in Ca may be explained by ion exchange with the rock due to variable salinity.

All waters are highly undersaturated with respect to gypsum, and highly to fairly undersaturated with respect to calcite and dolomite (Table 6). This means that carbonate precipitation is not to be expected in the aquifer, although it may happen in the closed lagoons. Equilibrium CO_2 partial pressure (log) range is −3.2 to −1.9 (Table 6) with most values clustering around −2.8 to −2.6, or one order of magnitude higher than the atmospheric value. This shows a moderate influence of soil CO_2 or a closed system evolution. Waters from the lagoons and lava tube drippings C-3 show soil effect or a biologically generated CO_2 source. Water from lava tube drippings C-1 and C-2 are like the other groundwater samples and show a moderate addition of soil CO_2.

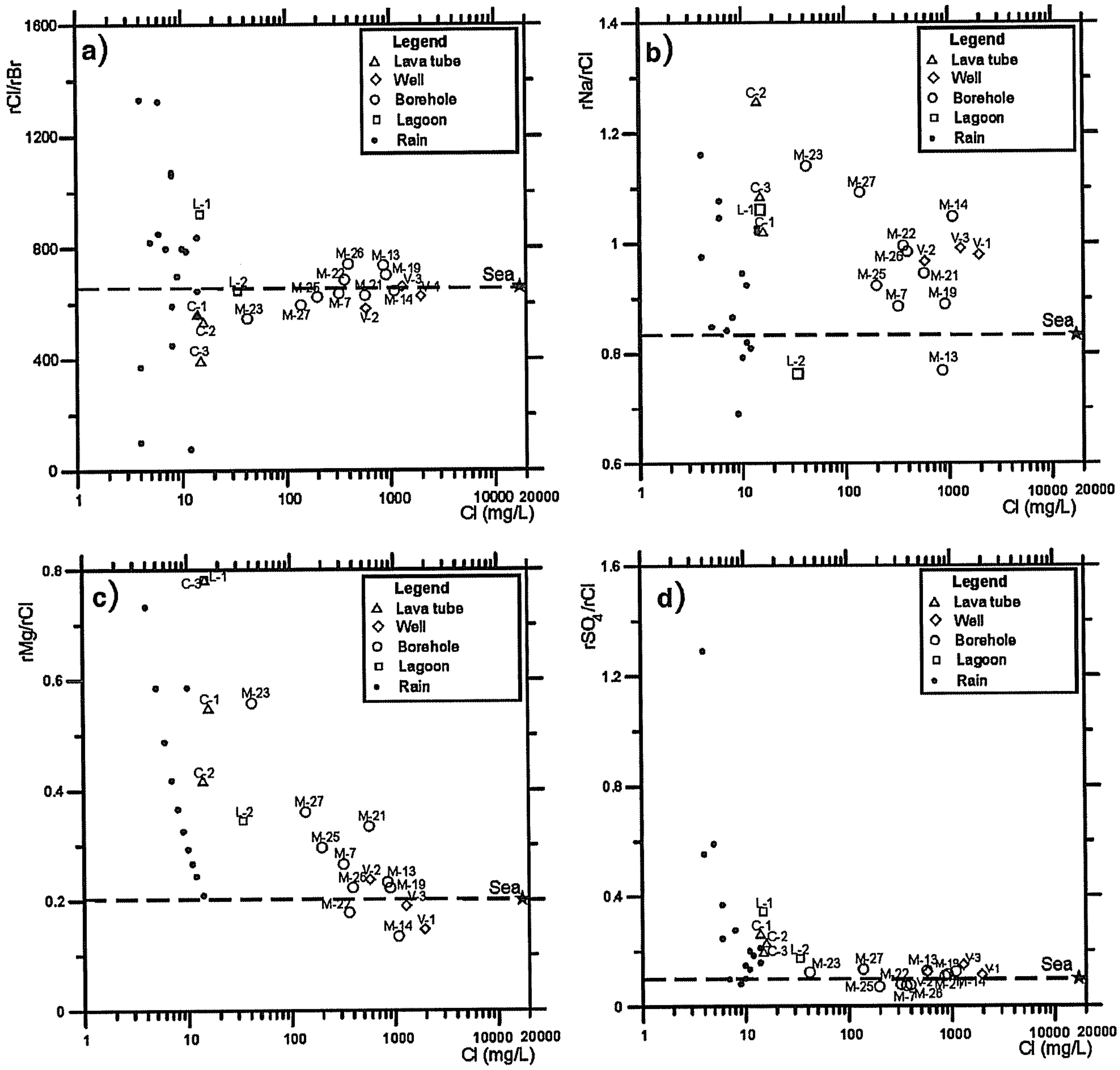

Fig. 5 **a** rCl/rBr, **b** rNa/rCl, **c** rMg/rCl and **d** rSO_4/rCl ratios of rain, lagoon, lava tube and groundwater samples from Easter Island v. Cl content. The prefix '*r*' means that concentrations are in meq/L. The *horizontal lines* show the typical ratio for seawater. Seawater is indicated by an *asterisk*

The chemical composition of flowing Rano Aroi lagoon (L-2) water is closer to groundwater than that from lava tube drippings and the Rano Kau lagoon. This means that it may represent the discharge of a more or less stable groundwater body, a perched one or the result of a high saturated zone, if there is a volcanic core of low permeability volcanics there. Since it is near the top, it is easily subjected to seasonal variations, and even desiccation. The saturated zone hypothesis presents doubts: with the existing high groundwater recharge, other springs are expected to exist, especially towards the northern sector, but the hypothesis cannot be definitively discarded with existing data, since it depends largely on rock permeability and the cover of young volcanics.

Environmental isotopes

Water isotopic data shows that Rano Kau lagoon (L-2) is closed and evidences evaporation of accumulated rainfall (Fig. 4). In contrast, Rano Aroi lagoon (L-1) is located next to samples of groundwater, thus indicating its renovating underground origin. Lava tube drippings at low altitude (Rohio C-1 and C-2) are isotopically heavier than water from the lava tube near Terevaka summit (C-3) at a higher elevation. Borehole and well water data are in between and close to the world mean meteoric water line (Fig. 4). This may indicate a preferential recharge at intermediate and high altitude, although further information is needed to check this assumption. The displacement from the world mean meteoric water line of some groundwaters points to a lower deuterium excess that may be the result of local rainfall characteristics. Groundwater from the northern (Anakema) and the eastern areas (western slopes of Poike) are isotopically the heaviest, and consequently they are assumed to be recharged at relatively low altitude. Groundwater from the southern slopes of Terevaka (Vaitea) and the western sector of the island are lighter and consequently assumed to be recharged at higher altitude.

Lava tubes C-1 and C-2 have an altitude of 120 m asl and $\delta^{18}O \approx -2.1‰$, and lava tube C-3 is at an elevation of 350 m asl and $\delta^{18}O \approx -3.5‰$. This gives a vertical isotopic gradient of about −0.6% per 100 m, which seems too high when compared with other islands such as Gran Canaria (Gasparini et al. 1990), Cheju (Davis et al. 1970), Mount Etna (D'Alessandro et al 2004) or Hawaii (Scholl et al. 1996, 2002), where the gradient is −0.15 to −0.3‰/100 m, as also happens in many other situations (Gonfiantini et al. 2001). New sample rounds are needed to correct the value or to determine if there is some local effect or simply that the used values are occasional results that differ from the average ones.

Water isotopes are not able to clearly show if there is some mixing with seawater. Changes are of the same order as analytical uncertainty. The strontium isotopic composition of Easter Island groundwater is between that of oceanic basalts and seawater. All measurements in Easter Island basalts cluster around 0.7030 (Bonatti et al. 1977; Cheng et al. 1999; Derruelle et al. 2002). Other volcanic rocks that are less frequently found in the island such as trachytes and rhyolites also have a $^{87}Sr/^{86}Sr$ ratio close to that of the basalts (0.7029–0.7040). The value for seawater is 0.7092. Sample C-1 from one of the Rohio lava tubes, representing recharge water, has a $^{87}Sr/^{86}Sr$ value of 0.70506, higher than the island's rock values. This increase may be the result of incorporating Sr of marine origin through atmospheric fallout. This coincides with observations made by Cheng et al. (1999), who found that volcanic rocks from the surface had a $^{87}Sr/^{86}Sr$ ratio higher than that of deeper samples.

Figure 6 shows the ratio $^{87}Sr/^{86}Sr$ vs. the inverse of strontium concentration. A mixing line connects the seawater value with a lithologic value representative of the island rock Sr contribution. This indicates that salinity

Table 6 Calculated logarithmic saturation indices and logarithm of equilibrium CO_2 partial pressure (atmospheres) from analytical data from the May 2002 field sampling

Sample	Saturation index (log)			Equilibrium		
	Calcite	Dolomite	Magnesite	Gypsum	PCO_2 (log)	*R*
C-1	−2.7	−5.0	−2.8	−4.1	−2.9	1.8
C-2	−3.0	−5.4	−3.0	−4.4	−3.2	1.3
C-3	−3.1	−5.8	−3.3	−4.1	−2.0	4.5
L-1	−4.8	−8.7	−4.5	−4.3	−1.3	9.0
L-2	−5.8	−11.0	−5.7	−4.0	−0.9	13.5
M-13	−0.7	−0.8	−0.7	−2.0	−2.7	2.2
M-14	−0.8	−1.2	−1.0	−1.9	−2.6	2.4
M-19	−1.0	−1.4	−0.9	−2.1	−2.6	2.4
M-21	−0.5	−0.5	−0.6	−2.1	−1.9	5.0
M-22	−0.9	−1.2	−1.0	−2.7	−2.6	2.4
M-23	−1.2	−2.0	1.3	−3.7	−2.6	2.4
M-25	−0.7	−1.0	0.8	−2.9	−2.7	2.2
M-26	0.8	−0.9	−0.7	−2.8	−2.8	3.7
M-27	−1.6	−2.7	−1.7	−2.9	−3.2	1.3
M-7	−0.8	−1.3	−1.0	−2.6	−2.4	3.0
V-1	−0.5	−0.4	−0.5	−1.6	−2.9	1.8
V-2	−0.9	−1.1	−0.9	−2.2	−2.4	3.0
V-3	−0.4	−0.4	−0.5	−1.7	−2.6	2.4

R is the ratio of calculated water CO_2 partial pressure to atmospheric CO_2 partial pressure increase may be of marine origin. C-1 is off this line and can be explained as corresponding to a weaker water–rock interaction, relative to atmospheric Sr contribution. The same can be said for the M-7 sample, which probably receives a higher Sr contribution from the rock. Boreholes near the coast show $^{87}Sr/^{86}Sr$ values that are closer to the marine ratio than those further inland, which have a value approaching that of volcanic rocks. Samples with a higher chloride content (not shown) have a greater $^{87}Sr/^{86}Sr$ ratio, and consequently are close to the seawater value. This means that the increase of salinity may be due to mixing with seawater, as also shown by chemical values.

The isotopic results for dissolved sulphate are depicted in Fig. 7. As SO_4 increases, the $\delta^{34}S$ approaches the marine value (Fig. 7a). Deviations may be due to SO_4 isotopic fractionation in sea spray ($\delta^{34}S$=20–22‰), which contributes to coastal atmospheric SO_4. The higher the SO_4 content in well water the higher the direct marine contribution. Borehole 23 sample has the lowest sulphate content and the lowest $\delta^{34}S$ (+18.9‰) which reflects the contribution of background atmospheric sulphur. Its isotopic composition seems to respond to the $\delta^{34}S$ value that is characteristic of recharge water, which incorporates sulphate of marine origin from the marine aerosol (Dogramaci et al. 2001; Herrera and Custodio 2003). The plot of $\delta^{18}O$ of dissolved sulphate vs. sulphate (Fig. 7b) shows a slight increase of $\delta^{18}O$ over the seawater value. This may be explained by atmospheric contribution of SO_4 resulting from oxidation of background atmospheric sulphur by atmospheric oxygen ($\delta^{34}S$=+23‰) (Van Stempvoort and Krouse 1994). Groundwater samples with the highest dissolved sulphate have $\delta^{18}O$ sulphate values that approach the seawater value, again indicating direct seawater contribution. The plot of $\delta^{18}O$ vs. $\delta^{34}S$ in dissolved sulphate (Fig. 7c) shows some slight deviations with respect seawater, according with what has been said before. There is an excess sulphate contribution relative to seawater dilution, indicating the background atmospheric contribution, as can be seen in Fig. 5d.

The interpretation of $\delta^{13}C$ values is unclear due to the scarce data available. Water collected from pools at the C-3 lava tube floor shows $\delta^{13}C$ around −20‰, which is to be expected from an eucalyptus tree forested area in which ground is devoid of carbonates and soil CO_2 is dissolved in almost closed conditions relative to CO_2. This is also the case of the Doñana area, southern Spain (Iglesias 1999) or in the forested area of Gomera, Canary Islands (Custodio and Manzano 1992). This may agree with CO_2 rich soil receiving quite a high recharge, so it becomes close to water saturated conditions when it rains.

The Rohio area lava tubes have a heavier $\delta^{13}C$ value of −9 to −14 ‰, which may be the result of soil CO_2 dissolution in an open system relative to CO_2. This means less recharged areas and/or with higher soil permeability (young lavas), although some atmospheric influence (atmospheric $\delta^{13}C$=−8‰) is possible, both in the soil and inside the lava tube. In fact, equilibrium partial pressure of soil CO_2 is only slightly above the atmospheric value.

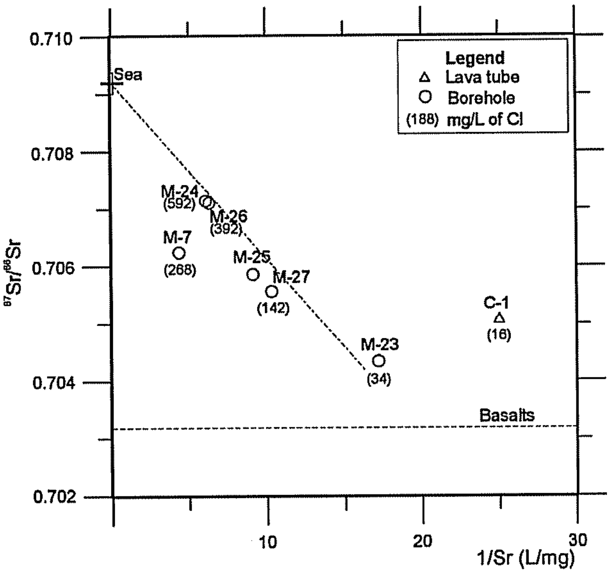

Fig. 6 Strontium isotope composition of groundwater from Easter Island versus 1/Sr (L/mg). The *horizontal lines* indicate the typical isotopic ratio for basalts, and the + indicates the typical value for seawater. Different mixing lines are possible depending on initial Sr content

Groundwater is heavier in ^{13}C, clustering around −6 to −9‰. Waters with a higher salinity apparently tends towards a heavier value. These values may represent recharge in open conditions to soil CO_2. Total dissolved carbon (dominantly HCO_3) is isotopically fractionated with respect to soil CO_2. This has been observed in the recent Fuerteventura Island lava fields and also in Gomera Island (Canary Islands). Furthermore, there is the possibility of dissolving carbonate remnants in the ground, of marine (shell fragments in present or deep beach sediments) or volcanic origin (fissure deposits from hot fluids). Their $\delta^{13}C$ can be expected to be low, around 0‰. Water chemistry favours this possibility. Volcanic CO_2 contribution would produce heavier $\delta^{13}C$ values and higher HCO_3 contents, as in Tenerife Island, Canary Islands (Custodio 1978).

In deep boreholes, tritium tends to decrease as the thickness of the unsaturated zone increases. However, it should be considered that differences in tritium content may be also related to heterogeneities of the medium in the unsaturated zone (Cook et al. 2005).

Easter Island tritium data in precipitation were completed with data from the Cook Islands station (21°5′S, 159°8′W), which is the station closest to Easter Island in the IAEA network, and there are similar characteristics with regards the oceanic environment and geographical emplacement.

To estimate water turnover time in the aquifer, the code MULTIS (Richter et al. 1992) has been used. The code uses two extreme mixing models: exponential and piston flow, and allows combining these models in different ways, in series and in parallel, and allows both direct and inverse calculations. The results from modelling (Herrera et al. 2004, 2006) show that in Easter Island waters, infiltrating the soil takes 2–3 years to go through the unsaturated zone soil above the lava tubes. Borehole waters have a residence time ranging from 5 to 50 years. At large scale this agrees with what can be expected from piston flow and distributed recharge, taking into account that the unsaturated zone thickness in the island apron may exceed 100 m (borehole M-23), and the average volumetric water content is estimated at 0.05–0.1, and there is a high recharge rate.

The relatively high tritium values found in some boreholes may be due to preferential vertical flow through rock fractures, provided that the high recharge rate keeps rock matrix and low permeability interlayerings at quite high relative water saturation. This is what seems to happen in the thick Amurga phonolitic massif in southern Gran Canaria (Custodio and Custodio 2001), or when fractures are recharged by ponding water at the surface (Faybishenko et al. 2000), by drainage from the soil, or by contribution from intercalated low permeability layers (Flint et al. 2001). Very low permeability fissure coatings, which tend to reduce water soaking (Soll and Birdsell 1998) does not seem probable.

A large part of the slope areas of Easter Island seems to correspond to a piling of recent, very permeable subaerial lava flows, with an unknown although probably large thickness. The existence of a low permeability volcanic core above sea level is not clear, although this may happen under the volcanic edifices. This is a main unsolved question, although the core is found in other volcanic islands up to some height, as in El Hierro Island, Canary Islands. If volcanic feeding dikes follow a radial pattern, associated fissures help in draining groundwater towards the periphery. This may be the case of Easter Island. Consequently, in a large area around coastal Easter Island, a freshwater lens floating on saline water can be expected, as happens in classical oceanic islands (El Hierro in the Canary Islands, the Pearl Harbor aquifer in Oahu, Hawaii Islands, and the periphery of Réunion). The characteristics and thickness of the freshwater–saltwater mixing zone is unknown, but it may be quite thick as occurs in Pearl Harbor (Gingerich and Voss 2005) and is also the case in the coastal areas of other islands such as the Azores (Cruz and Silva 2000).

In spite of the small borehole penetration into the saturated zone, their water salinity suggests an important thickness of the mixing zone between fresh and marine water. Taking into account that the theoretical freshwater lens thickness has been estimated to be 50 m in the central slopes of Terevaka volcano (Vaitea) and that this thickness decreases progressively towards the shore, the contribution of salinity from the lower part of the aquifer is possible as a consequence of intense hydrodynamic dispersion processes due to large heterogeneities and water-table fluctuations. The accuracy of water-table elevations above the effective, local mean sea level is also a concern. Errors may modify expected theoretical thickness of the freshwater body.

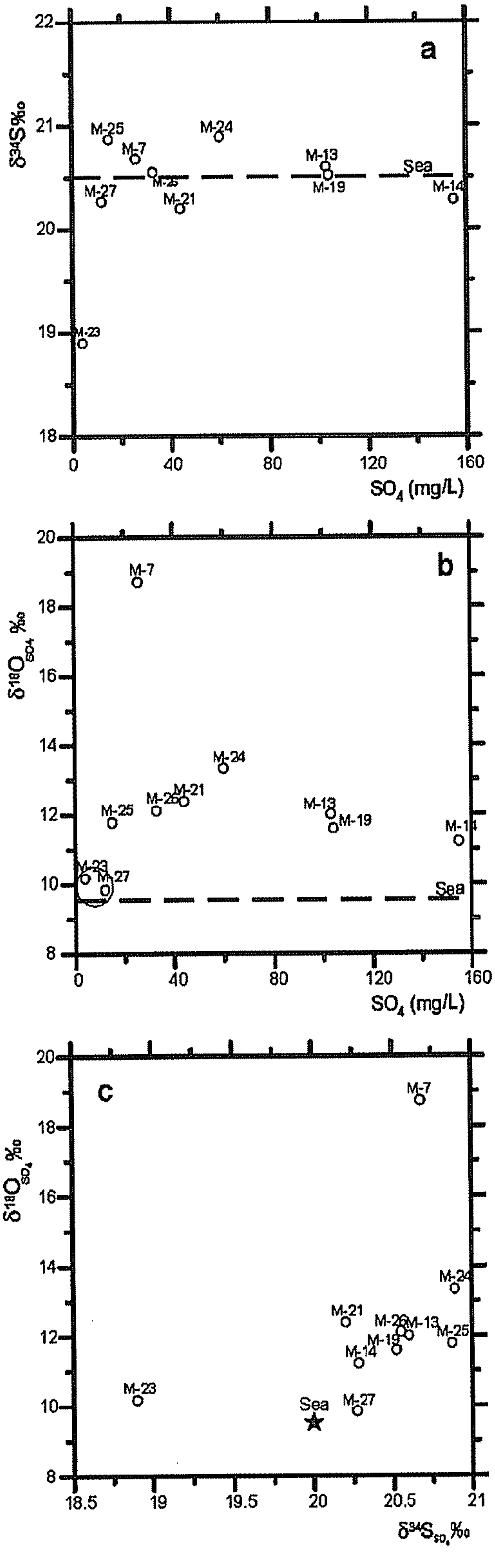

Fig. 7 Plot of **a** $\delta^{34}S_{SO4}$ and **b** $\delta^{18}O_{SO4}$ vs. SO_4, and **c** $\delta^{18}O_{SO4}$ vs. $\delta^{34}S_{SO4}$ data of Easter Island water samples. Values for marine dissolved sulphate are indicated

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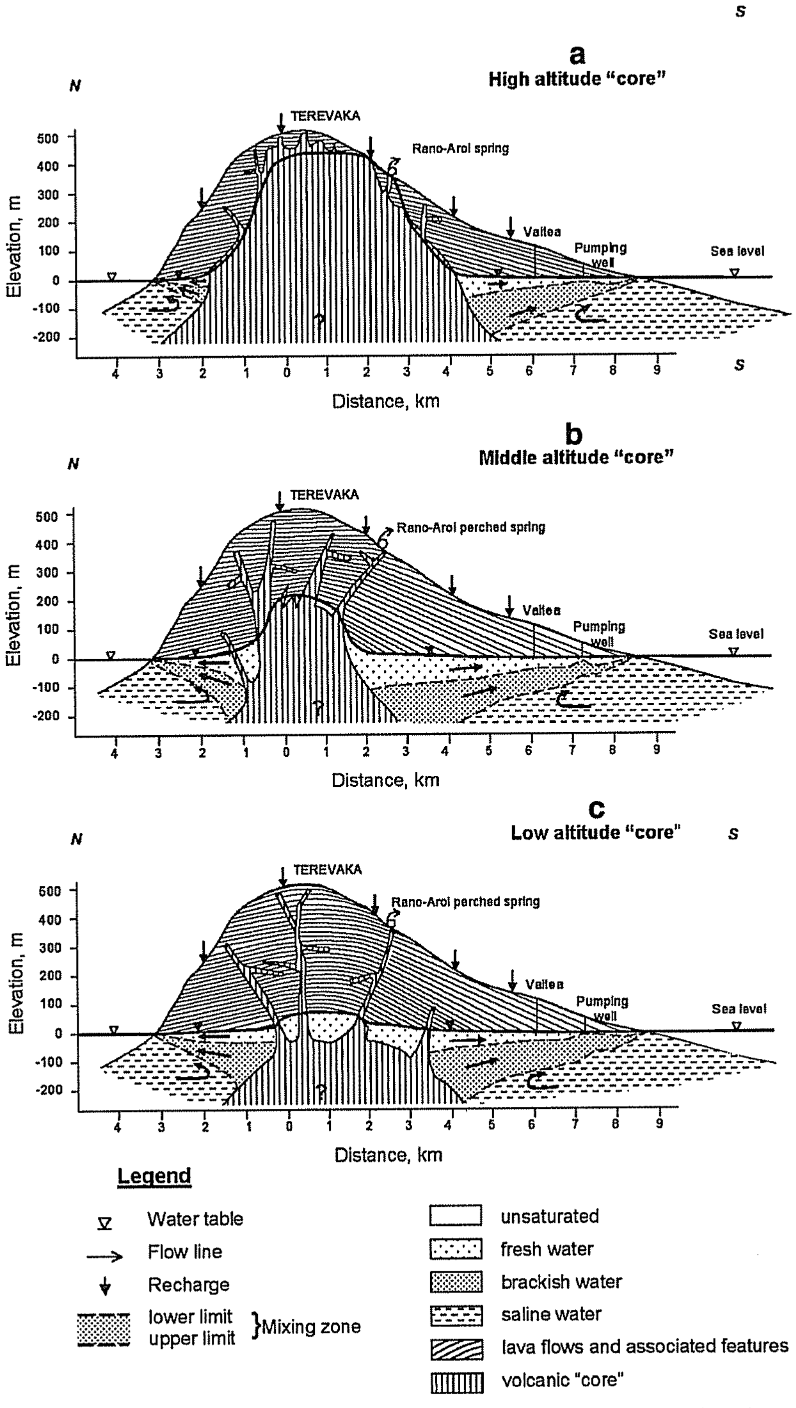

Fig. 8 North–South oriented hydrogeological cross-section sketches of Easter Island considering three hypothesis: **a** high altitude, not outcropping, volcanic core occupying a large part of the island; **b** middle altitude volcanic core leaving a thick unsaturated zone; **c** low altitude volcanic core. The freshwater, brackish and saline water bodies are indicated schematically

Conclusions

By combining coastal water table and permeability data with chemical and isotope analyses of well and borehole water seepages and drippings inside volcanic tubes, it is possible to advance in the conceptual hydrogeological model of the small, pervious volcanic Easter Island. The model can be applied to other small, pervious small islands. This can be done in spite of wells and boreholes being located near the coastal area, provided that small inland seepages and lagoons, and also rainwater, are also sampled. A key hydrogeological feature is the probable existence of a low-permeability volcanic core and its altitude. Geological surveys on the surface do not allow one to locate the possible emplacement of the core.

As shown in Fig. 8, in Easter Island, the existence of a low-permeability core of altered, dike injected and older volcanics inside Terevaka volcano, the dominating volcanic edifice, is uncertain, as that also depends on their altitude. Three possibilities are shown schematically. Actual circumstances may be much more complex. There is an apron of young to relatively young volcanics forming the slopes and the coastal area which behaves as a highly transmissive aquifer containing a thin freshwater lens floating on intruding seawater and separated by a thick freshwater–saltwater mixing zone. This is a common circumstance in many volcanic islands. Aquifer thickness is not known but is probably large.

Average recharge is estimated to be around 300–400 mm/year, higher at the top and lower at the coast. The simple application of Darcy's law along the coast allows for an estimation of the total freshwater outflow along the shore. Uncertainties in the transmissivity values and hydraulic gradients only allow for a crude result, about 50–60 Mm^3/year, irregularly distributed. These figures are in agreement with the total recharge expected. Actual groundwater abstraction is poorly known but it is probably in the range of 0.5 to 1 Mm^3/year, much lower than the recharge. Consequently, the island as a whole is little disturbed by abstraction. However, groundwater abstraction is concentrated in some areas at the coastal zone, so local brackish water upconing from the freshwater–saltwater mixing zone can be expected.

Chemical and isotopic environmental analyses point to and confirm the marine origin of pumped water salinity, which may attain or exceed 1,000 mg/L Cl, while recharge water is in the range of 15 to 40 mg/L Cl. Tritium values, not fully commented on here, agree with the unsaturated zone thickness and flow in the aquifer, with turnover times of 10–50 years. The very small penetration of wells and boreholes does not allow for an estimation of the freshwater lens volume.

The existence of a low-permeability core and its elevation relative to mean sea level is an important issue from the practical point of view. The core comprises volcanic chambers and main fracture zones which are thermally and hydrothermally altered. The role of dikes and sills may be highly variable, although probably reduce flow in such very permeable lava flow pilings. Since there are no deep boreholes in the appropriate areas, geophysical surveys are an alternative to try to get additional knowledge, especially the audiomagnetotelluric method. This has been carried out in La Fourneuse volcano, in Réunion Island (Courteaud et al. 1997; Descloitres et al. 1997), which has some similarities with Terevaka volcano, although much higher.

Easter Island represents many of the common features of other small volcanic islands such as the Galapagos Islands (Equador) and many of the small Japanese, Philippine, Indonesian and Polynesian Islands, which share a small surface, high altitude area and a dominating young strato-volcano with little erosion reshaping. Combining near-the-coast hydrogeological information with chemical and isotopic data on water from rainfall, spring, leakages, wells and boreholes, the conceptual hydrogeology model can be more precisely formulated and are a help in groundwater resources knowledge, development, protection and management.

From a practical point of view, and according to the simplified conceptual hydrogeological model of Fig. 8, in order to improve salinity of pumped water, boreholes should be further inland, although this means a higher cost of drilling and pumping, and perhaps there is the risk of finding low permeability formations. An alternative could be doing as the Canarians do on their islands: excavating shafts down to the water table and then constructing drainage galleries or horizontal boreholes. This is the same solution adopted in former times by British rulers in Malta Island (Mediterranean Sea); in this case, in highly permeable limestones. However, this is currently a costly solution, if feasible at all. Drilling water galleries may be interesting only if the core is high enough and there are "palaeovalleys", although flows may sharply decrease with time.

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