Origin and residence time of water in the Lima aquifer[i]

Modesto Montoya[1,2,*], Enoc Mamani[1]

[1] Instituto Peruano de Energía Nuclear, Canadá 1470, San Borja, Lima, Perú
[2] Universidad Nacional de Ingeniería, Av. Túpac Amaru 210, Rímac, Lima, Perú

Resumen

Los 8 millones de habitantes de la costera ciudad de Lima son abastecidos con agua del río Rímac y de pozos en el acuífero de Lima. El caudal histórico del río Rímac y el nivel estático histórico de los pozos de agua son correlacionados para calcular el tiempo de residencia del agua en el acuífero desde que es recargado por el río Rímac hasta que llega a un pozo situado a 12 km, en el distrito de Miraflores, cerca del mar. La abundancia relativa de ^{2}H y ^{18}O son usados para identificar los orígenes de las aguas de esos pozos; y los contenidos del ^{3}H y ^{14}C son usados para estimar el tiempo en que cayeron como parte de la lluvia.

Abstract

The 8 million inhabitants of the coastal city Lima are supplied with water from the Rimac and Chillon rivers and water wells in the Lima aquifer. The history of the Rimac River flow and static level of water in its wells have been correlated to calculate the residence time of water in the aquifer it is recharged by the Rimac River until it reaches a well located 12 km away in the Miraflores District near the sea. The relative abundance of ^{2}H and ^{18}O are used to identify the origins of the waters from those wells, and the ^{3}H and ^{14}C contents are used to estimate the time after they fall as rain.

Keywords: Lima aquifer, Water, Time residence

1. Introduction

The purpose of this paper is to study the evolution of the Lima aquifer dynamics. This aquifer is exploited by the Lima Waterworks Company (SEDAPAL) to supply the growing population of Lima, which had nearly 8 million inhabitants in 1997.

In 1992, Lima's water demand was 24.8 m^3/s, and it was satisfied with surface water from the Rimac River (9-13 m^3/s) and aquifer (up to 9.5 m^3/s) replenished by the Rimac and Chillon rivers. A 2.2 m^3/s overexploitation with an increasing trend was observed.

In 1997, the exploited amount of groundwater reached 12.38 m^3/s; the same year, projects were initiated to determine a more rational use of groundwater and methods to artificially recharge the Rimac aquifer and switch from groundwater to surface water (Quintana and Tovar, 2002).

To evaluate the effects of those projects, SEDAPAL measured the evolution of the static level of Lima's water wells. To study the origin of the water in the aquifer, the relative abundance of ^{2}H and ^{18}O were measured, and the water residence time in the aquifer was estimated from the contents of ^{3}H.

2. The Rimac Basin

Peru is located along the west coast of South America from 3° to 18° south latitude, and it has three distinguishable regions: Costa, Sierra and Selva. The Costa region comprises the coast limited by the Pacific Ocean; the Sierra region contains the Andean Mountains, which has glaciers above 6000 m; and the Selva region is the western region of the tropical Amazonas basin. The rainy season in the Sierra is from December to March and results in significant fresh water flow to the region's rivers, most of which are tributaries to the Amazon River with the remainder flowing to the Pacific Ocean in several drainage basins. Lima City is located along the central part of the coast and irrigated mainly by the Rimac River, whose slope is more than 3 %. The Rimac River flows from the wetlands, small lakes and glacial meltwaters of the Cordillera Central through the steep narrow valleys onto a clastic wedge

* Corresponding author: mmontoya@ipen.gob.pe

of coarse alluvial sediments between the mountains and coast (Leavell, 2008).

The Rimac basin has a length of 204 km, average width of 16 km and surface of 3398 km^2. Its borders are the Mantaro Basin to the northeast, Lurin Basin to the southeast, Chillon Basin to the northwest and Pacific Ocean to the southwest (INGEMMET, 1988). The Rimac River drops from 5000 m above sea level and flows down 145 km before discharging into the sea. Its main tributary is the Santa Eulalia River.

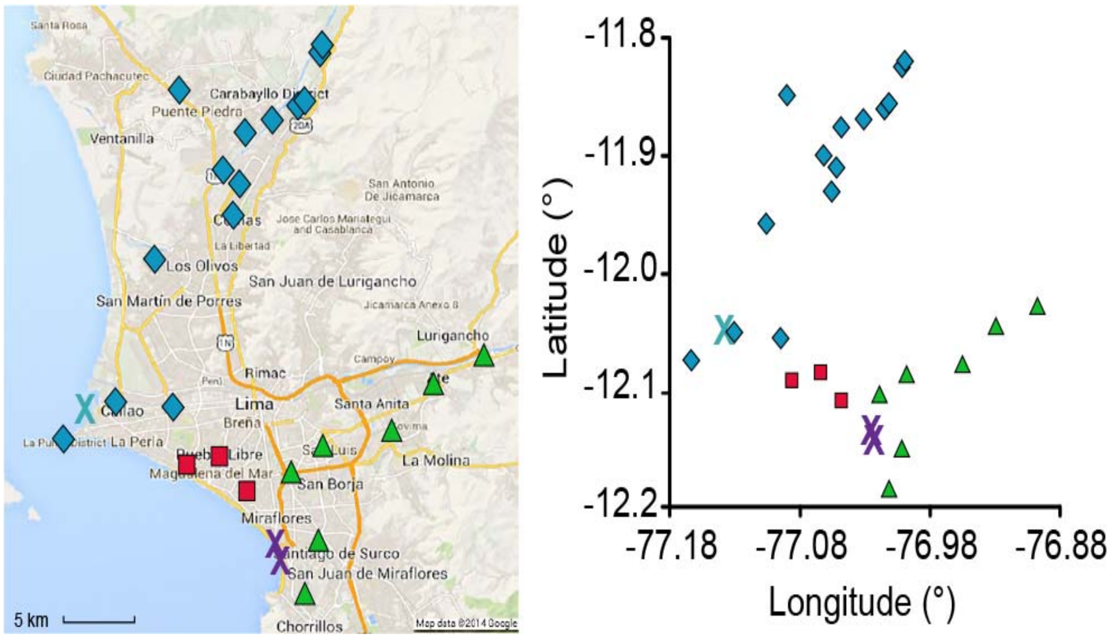

Figure 1. Satellite image of Lima City. The Lima delta is indicated by a triangle formed by the Rimac River to the north that flows from east to west, crosses Ate and Lima and discharges to the sea in front of Callao. The Rimac River replenishes the aquifer of the Lima delta in the northern part of Lima. The alluvial deposits from the Rimac basin decrease from east to west and are dispersed to the north and south of the Rimac River. The deposits from the Chillon basin decrease roughly from the north to south (left). The geographical coordinates of a group of wells used by the Lima Waterworks Company (SEDAPAL). The diamonds correspond to wells located mostly in the basin of Chillon, the triangles correspond to the Rimac basin, and the squares correspond to waters supplied from both basins. The blue cross refers to a well in the seabed. The purple crosses represent the Estrella spring (left) and Barranquito spring (right) on the beach at Costa Verde. A well in the sea is identified by an asterisk (right).

Climates, rainfall and temperature

Because of the cold Humboldt Current, Lima's climate is cooler than cities of the same latitude and altitude in other parts of the world. Its precipitation is 21 mm annually, and at altitudes from 1000 m to 2000 m above sea level, there is a low intensity rainy season from December to April. At altitudes from 2000 m to 3500 m, the precipitation is 250 mm annually and occurs from December to March. From 3500 m to 4000 m, precipitation occurs from December to March, and the annual rainfall is over 450 mm. Over 4000 m, the rainfall can reach 750 mm annually, and the nighttime temperatures average 4C (INGEMMET, 1988).

Geological characteristics

The Rimac basin geological structures are composed of sedimentary, metamorphic, volcanic and intrusive rocks of the Jurassic and Quaternary. Folds, faults and plutonic and hypabyssal masses can be distinguished, and two geological zones are identified: the Occidental Zone, which is formed by with bodies of igneous, sedimentary and metamorphic rocks; and the Oriental Zone, which is formed by rocks of the Jurassic, Cretaceous, Tertiary and Quaternary (INGEMMET, 1988).

Hydrological description

The Rimac Hydrographic Basin covers an area of 3398 km^2 and has an average gradient of 3.23% (INGEMMET, 1988), 2237.2 km^2 permanent precipitation and 895.2 km^2 intermittent precipitation (CESEL, 1999). The Rimac River has 23 tributaries, and the main tributary is the Santa Eulalia basin, which has an area of 1097.7 km^2 (CESEL, 1999). The top lines of the Rimac´s tributaries are between 4400 m to 5200 m (Rojas *et al*., 1994).

The dry lower zone of the Rimac Basin is formed by the Lima's entrance to its mouth at the Pacific. This zone is 17.5 km long with a gradient of 1.1% and altitude of 195 m above sea level (Rojas *et al*., 1994).

3. Hydrogeological description of the Lima aquifer

The Lima aquifer is formed by unconsolidated alluvial and interspersed layers of gravel, sand, silt and mudstone that are deposited over a low permeability material, which is bounded by volcanic-sedimentary rocks and granites in the substrate. The Lima aquifer has an area of 260 km^2 with a maximal thickness estimated between 400 m to 500 m (INGEMMET, 1988).

The Lima aquifer is recharged with rains at the upper regions of the Rimac and Chillon basins. There is also a contribution of the Rimac and Chillon rivers through filtrations, garden watering and irrigation canals. These flows reach the lower levels of the water table on the ends of the bay. At the sea to the front of Callao, there is a well that is pumped to supply water to ships. In Chorrillos, there is another water well whose floor is below sea level.

The permeability in the valley is 1 x 10^{-3} m/s and changes to 10^{-4} m/s in the alluvial cone. The storage coefficient is 5% in the valley and 0.2% in the coastal area (INGEMMET, 1988).

The upper part of the Lima aquifer is mainly composed by a nearly 100 m layer of gravels and other coarse-grained sediments in a sand and clay matrix interspersed with fine-grained layers. The lower part is formed by much finer unconsolidated sediments composed of sands, silts and mud. The greater part of the aquifer is mostly unconsolidated alluvial deposits. Between the Rimac and Chillón rivers, the upper part of the aquifer is formed by fine-grained deposits (Rojas *et al*., 1994; Méndez, 2005).

4. Lima Delta

On the surface of the Lima aquifer, a delta with the shape of an equilateral triangle can be found. The triangle is formed by a) 20 km of the Rimac River, which contributes to replenishing the aquifer and flows from east to west at a -12° latitude; b) the Surco channel, which begins at a -76.90° latitude and flows from the northeast to southwest and c) the Pacific coast, where the aquifer discharges (Fig. 1).

The northern part of the Lima delta also receives a contribution from the Chillon River. The east end of the Rimac River at the delta has an altitude of 300 m above sea level. In the middle section of the northern side of the Lima delta, the Rimac alluvial deposits are joined by the Chillon alluvial deposits at 130 m above sea level; the topographic level subsequently decreases on both sides of the Rimac River, which suggests that the Rimac alluvial deposits descend from east to west and then disperse to the north and south sides. To the north at 8 km from the Rimac River, the ground level decreases to 66 m above sea level. The ground level rises to 130 m altitude at 25 km north of the Rimac River. Thus, near the Chillon River, the alluvial deposits from the Rimac basin are at higher levels than those from the Chillon basin.

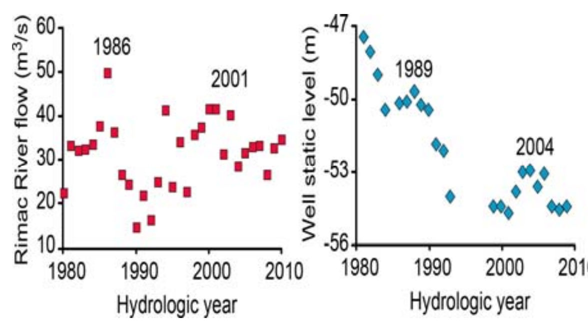

Figure 2. Historic flow (m^3/s) between 1980 and 2010 of the Rimac River in Chosica, 50 km east from the sea (left). Historic of the static level of well 71, which is 1 km from the Miraflores beach (right).

Water samples were collected from 25 wells and 2 water springs owned by SEDAPL, the locations of which are shown in Fig. 1 along with their geographical coordinates represented as longitude, latitude.

The beach forms a bay with a length of approximately 25 km between the water well referred to as La Punta (1) (coordinates -77.16°, -12.06°) and water well of Chorrillos (21) (coordinates -77.01°, -12.17°). At the Costa Verde beach, which is close to Chorrillos, a cliff with a height of 60 m is formed. At the base of the cliff by the sea, the Estrella water spring (19) (coordinates -77.02°, -12.14°) and Barranquito water spring (20) (coordinates -77.01°, -12.17) are found.

Residence time of water in the Lima aquifer

The Rimac River flows from east to west and replenishes the northern part of the water table over the Lima delta. There is a well located 1 km northeast from the Estrella spring. This water well, referred to as number 71 by SEDAPAL, had a static level of -33 m in 1966 and - 58 m in 1990; the well stabilized at - 58 m, which was most likely because the wells of the Lima aquifer could not extract water at this level.

The Rimac River flow reached a maximum historic level in 1986, which was reflected in a maximum historic of static level in well 71 in 1989. Similarly, the flow of the Rimac reached another maximum level in 2001 that resulted in a maximum static level in well 71 in 2004 (Fig. 2).

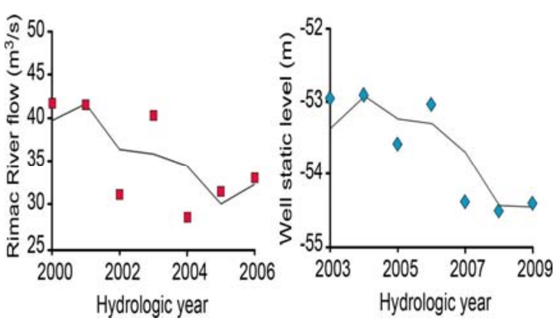

Figure 3. (Left): The same as in the left of Fig. 2 but for the period 2000 – 2006. (Right): the same as in the right of Fig. 2 but for the period 2003-2009. There are similar static level fluctuations delayed from the flow fluctuations by 3 years.

Annual variations of the Rimac River flow in the period from 2000-2006 are reflected in the annual static-level variations of well 71 for the period 2003-2009 (Fig. 3). This result suggests that the water infiltrating from the Rimac River in the water table under the Lima delta takes approximately 3 years to reach the Estrella water spring near the sea.

Origin of the water

The origin of the water is determined by the natural tracers ^{2}H and ^{18}O, which are stable isotopes. The composition of these isotopes in the water are expressed in terms of $\delta\ ^{18}$O and $\delta\ ^2$H, which are expressed in units of ‰.

The Lima aquifer receives contributions from the Chillon and Rimac basins. SEDAPAL has built water wells in both basins at altitudes higher than the Lima delta before the waters are mixed. The geographical coordinates of the SEDAPAL water wells are shown in Fig. 1. The corresponding isotopic composition of the water from these wells is shown in Fig. 4. The isotopic composition of the Chillon and Rimac basins are clearly distinguished as different columns on the δ-diagram.

The water in the aquifer under the Lima delta appears to come from both basins, except on the opposite sides of the delta. The water in the north side comes from the Chillon Basin, and the water in the south side comes from the Rimac Basin.

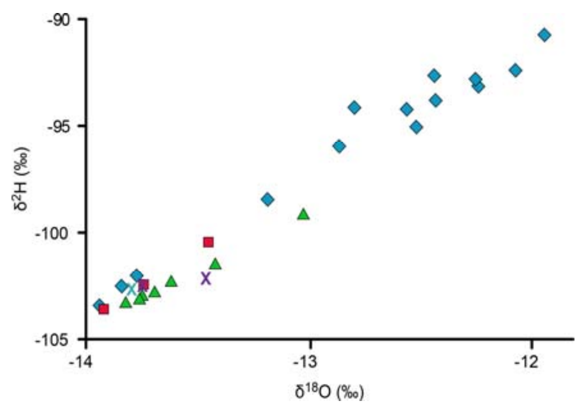

Figure 4. δ-diagram. Isotopic relative abundance in $\delta\ ^{18}$O and δ^2H of water corresponding to the wells presented in Fig. 2. The highest content of isotopes correspond to samples from the well at Puente Piedra 1, whereas the lowest content corresponds to a well at Callao, close to sea

The Estrella (upper purple cross in Fig. 1) and the Barranquito (lower purple cross in Fig. 1) water springs have isotopic compositions of -13.85 and -102.58 and -13.56 and -102. 32, respectively. The positions of these values on the δ-diagram (Fig. 4) suggest that the Estrella water spring is a mix of waters from the Rimac and Chillon river basins, whereas the Barranquito water spring only contains water from the Rimac basin.

The Pueblo Libre water well (16) has a water composition of -14.02 and -103.63, which resembles the parameters that characterize the waters from the Chillon basin (Fig. 4). The water well of Callao Sea (2) has a composition of -13.94 and -102.53, which resembles the parameters of the water from the Rimac basin. On the other side, the Puente Piedra well (6) has a composition of 12.03 and -90.76, which makes it the heaviest among the studied water samples.

Water weight affects the vaporization cycle of water, with lighter water falling as rain at higher elevations. This result suggests that among the collected samples, the waters of Pueblo Libre and Callao fell at the highest altitude and water from the Puente Piedra well (6) fell at the lowest altitude. The Puente Piedra well (6) is located on the right side of the Chillon River and separated from most of the samples that were collected from the left side of the river.

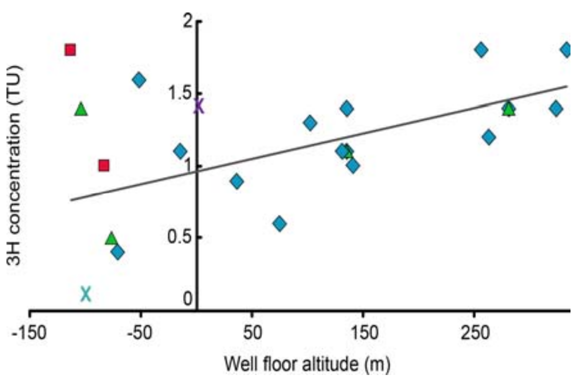

Figure 5. Tritium concentration in the water samples as a function of the altitude of the water well floor and corresponding to the wells represented in Fig. 2. For altitudes above sea level, the tritium content increases lineally with the water well floor altitude.

Water age

The well´s floor altitude can be defined as the altitude of the well minus the well´s depth. In Fig. 5, the tritium content, which is dependent on the altitude of the well´s floor, is plotted. Whenever the altitude is above sea level, the tritium content increases with the well´s floor altitude.

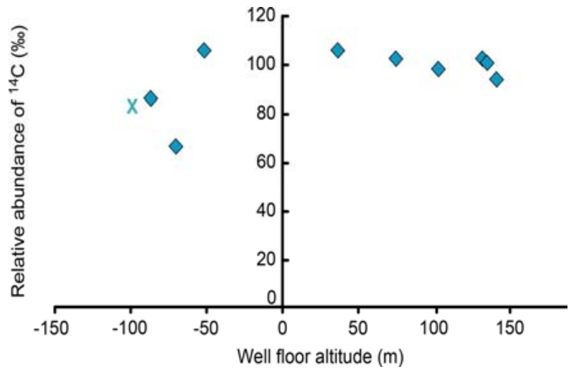

Figure 6. Relative abundance of ^{14}C as a function of water well floor altitude referred to some wells represented in Fig. 2. The lower content of ^{14}C in samples taken from lower altitudes suggests that those waters are older than the referred to samples taken above sea levels.

The water of the well under sea level in front of Callao is 0.1 TU with an error of 0.4 TU. The tritium half-life is 12.32 y, and the tritium abundance in fresh water in the region of study is 2 TU (personal communication of Rubén Rojas from IPEN, with information obtained from IAEA), then the water from this well has been under ground approximately more than 50 years. The water of the La Punta and Chorrillos wells have tritium levels at 0.4 with an error of 0.4 TU and 0.5 with an error of 0.3 TU, respectively, which suggests an age of more than 25 years.

Low ^{14}C content in the water of the wells (Fig. 6) appears to confirm the hypothesis that such water belong to the oldest water samples.

Oxygen content

In Fig. 7, the relative abundance of ^{18}O in the water as a function of the well´s floor altitude for the water wells located in Lima is plotted. Most of the wells in the Lima delta have floors below sea level. The abundance of ^{18}O in the water from the samples of the Lima delta are between -14.02‰ and -13.12 ‰. The sample from the Pueblo Libre well, whose altitude is -112.9 m, contains -14.02‰ of $\delta\ ^{18}O$, which is the lowest value obtained from all of the samples. The water sample from the Callao well, whose floor altitude is -15 m, contains -14.04‰ of $\delta\ ^{18}O$. This result suggests that these wells have the lightest waters, which indicates that the water fell as rain in the highest parts of the Rimac and Chillon basins.

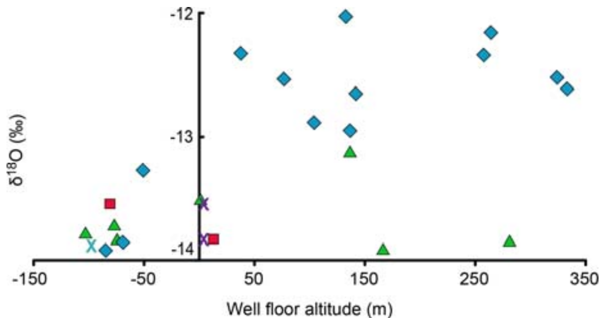

Figure 7. Relative abundance of ^{18}O in the water samples as a function of the altitude of the water well floor. Points refer to water wells represented in Fig. 2.

The water of the two wells of Ate Vitarte (26 and 27), whose floors are above sea level, have similar low levels of ^{18}O, which makes them exceptions among the wells with high altitudes. One of these wells has a floor at 166.2 m above sea level and contains -13.92 ‰ of $\delta^{18}O$, whereas the other well has a floor at 281.1 m above sea level and contains -13.86 ‰ of $\delta^{18}O$. These results suggest that these waters belong to the same aquifer layer whose waters reach the Callao and Pueblo Libre wells, which also have floors below sea level.

The ^{2}H and ^{18}O contents of the La Molina well (25) are separate from the Lima delta, and their values belong to the upper layers of the water table.

As shown in Fig. 7, the water from the Puente Piedra well (6), whose floor is at 131.55 m above sea level, contains -12.03 ‰ of $\delta^{18}O$, which corresponds to the heaviest water among the collected samples.

5. Conclusions

The Lima aquifer is formed by several alluvial layers that fell in a direction from east to west in the Rimac basin and north to south in the Chillon basin. This aquifer is recharged by rains on places with higher altitudes of the Rimac and Chillon basins as well as in higher parts of the Lima aquifer by those rivers.

The evolution of the static levels of the Lima delta (south of Lima) water wells correlated with the evolution of the Rimac River flow suggest that water in the aquifer recharged by the Rimac River has a residence time of approximately 3 years until it reaches the sea.

The relative abundance of ^{18}O and ^{2}H, which are expressed as $\delta^{18}O$ and $\delta^{2}H$ in units of ‰, in the water samples from the wells in the Lima aquifer, are distinguishable as two columns in the δ-diagram. Using these isotopes as tracers, the $\delta^{18}O$ and $\delta^{2}H$ values in the water samples from the Lima delta aquifer (south of the Rimac River) suggest a contribution from the Rimac and Chillon basins, with a higher contribution of the Chillon River in the northern region of the Lima aquifer and a higher contribution of the Rimac basin in the southern region.

The contents of ^{18}O and ^{2}H in a water sample, respectively, approximately depend linearly of the altitude at which fell that water as rain; a lower content corresponds to a higher altitude. Then, the $\delta^{18}O$ values suggest that waters taken from wells with above sea level of the well´s floor fell as rain at lower altitudes than the corresponding to waters taken from wells having undersea level of the well´s floor.

The ^{3}H content in the water from wells whose floors have altitudes below sea level and are located at the opposite ends of the beach indicated decades of residence time. The seabed well located to the northwest of the Lima delta has water that is more than 50-years old, and well located to the southwest of the delta has water that is 25-years old.

6. Acknowledgments

We would like to thank the International Atomic Energy Agency (IAEA) for the measurements of the ^{3}H and ^{14}C contents and SEDAPAL for the static level data of the wells. We also gratefully acknowledge the stimulating discussions with Ruben Rojas (IPEN), Edgar Alva (SEDAPAL), Fluquer Peña (INGEMMET), David Wahl and Carolina Aguilar.

7. References

[1]. CESEL. Monitoreo complementario de la cuenca del río Rimac. Dirección General de Asuntos Ambientales, Ministerio de Energía y Minas: Lima; 39. 1999.

[2]. INGEMMET. Estudio Geodinámico de la Cuenca del Río Rimac. (Boletín Nº 8b Serie C). Instituto Geológico Minero y Metalúrgico: Lima; 1988.

[3]. Leavell DN. The consequences of climate change for the water resources of Perú. In Proceedings, XIII World Water Congress. International Water Resources Association: Montpelier, France. 2008.

[4]. Méndez W. Contamination of Rimac River Basin Peru, due to Mining Tailings. Master's Thesis. TRITA-LWR Master Thesis LRW-EX-05-23. Lima, Peru; 31. 2005.

[5]. Quintana J, Tovar J. Evaluación del acuífero de Lima (Perú) y medidas correctoras para contrarrestar la sobreexplotación. Boletín Geológico y Minero. 2002; 113:303-312.

[6]. Rojas R, Howard G, Bastram J. Groundwater quality and water supply in Lima Peru. In: Nash H, McCall GJH (eds). Groundwater Quality. Chapman and Hall: London UK; 123. 1994.

[i] A previous version was published in http://arxiv.org/abs/1403.4974