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A perspective of alkaline Lonar Lake, Maharashtra, India with reference to its hydrochemistry

D. V. Reddy*, T. Madhav, P. Chandrakala and P. Nagabhushanam

CSIR-National Geophysical Research Institute,
Hyderabad 500 007, India

The inland Lonar Lake, encompassing a circular area of about 1 sq. km is situated in Buldhana district, Maharashtra state, India. The lake is part of the Lonar crater believed to have formed due to meteoric impact. It is third largest natural salt-water lake in the world. The lake water is not only saline, but also highly alkaline. In recent years, it is believed that the alkalinity and salinity of the lake water is being diluted with increased lake water level due to external inputs like seepage of water into the lake from nearby surface reservoirs. Studies on hydrochemical and isotopic signatures of lake water, and also lake water levels were carried out for one year to understand the lake dynamics. The generated data were compared with those available in the literature. This comparison showed that the water level and hydrochemistry of lake water are controlled by the local rainfall and evaporation, and that there are no other external water inputs to the lake.

Keywords: Alkaline lake, hydrochemistry, Lonar Crater, stable isotopes.

LONAR Lake located at 19°58′34.2″N lat. and 76°30′29.4″E long. is a near circular unique feature (Figure 1 *a*) located in Buldhana district, Maharashtra, India. The shallow, alkaline and saline lake is part of the Lonar crater in

*For correspondence. (e-mail: dvreddy.ngri@gmail.com)

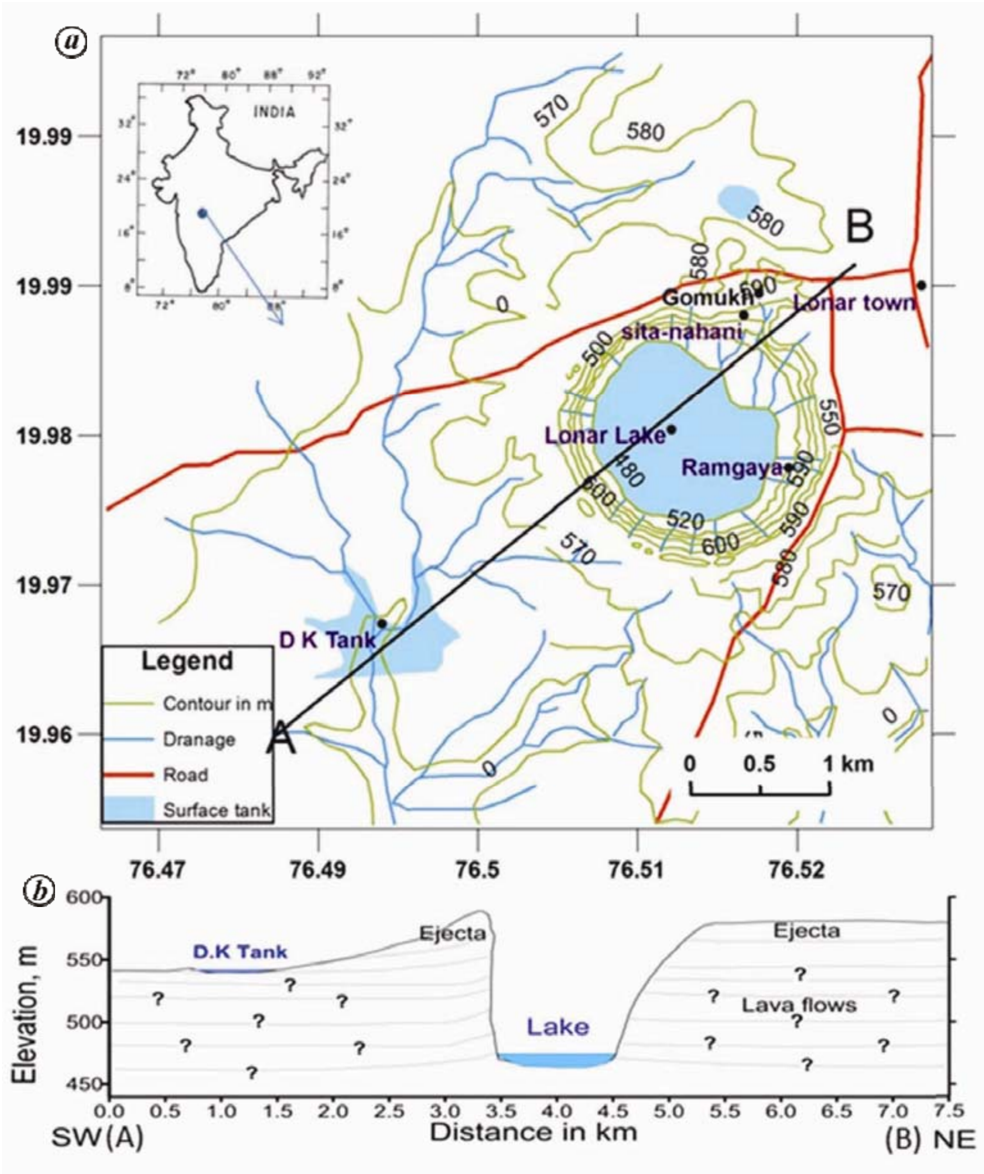

Figure 1. (***a***) Study area covering Lonar Lake. Deulgoan–Kundfal Tank (D–K Tank) and the surrounding areas. Three natural springs–Gomukh dhara, Sitra-nahani and Ramgaya are shown. (***b***) A topographic cross-section across (*A*–*B*) in the SW–NE direction across the Lonar Lake covering the surface tank and Lonar town.

the Deccan basaltic plateau. Though there are several theories about the origin of the crater[1–5], it is considered to be an impact crater[6–12]. The reported age of the impact crater is from few tens of ka (refs 10 and 13) to few hundreds of ka (ref. 14).

Blandford[2] during his short visit to the lake proposed that its high salinity could be due to accumulation of salts of evaporation process due to absence out flow from the lake. Due to the high alkalinity of lake water, crude soda was being recovered from the lake water for centuries[3]. In the highly alkaline environment, only distinct microorganisms can survive. Many studies were attempted on the biodiversity of the lake[15–18] and also one-time measurement of lake water quality. However, no detailed investigations were made combining the lake hydrology and hydrochemistry.

Based on a few reports[16,19] it is believed that the lake water level has increased and salinity/alkalinity reduced due to seepage of water from the surrounding surface water tanks.

The present study is aimed to understand the hydrology of the lake and external contributions (if any) to it and to identify the reasons for the long-term temporal variations in its alkalinity and salinity.

The circular Lonar crater is about 1800 m in diameter and 135 m deep with respect to crater rim (Figure 1 *a*) is located in the Deccan basaltic plateau. The plateau consisting of several horizons of lava flows, is of Cretaceous period. Regional topography around the crater is plateau-like, with occasional hillocks and erosional features. About 30 m thick ejecta around the crater formed as its rim. The surface water drainage system around the crater divides the area with a NW–SE trending topographic high north of the crater. From this division, two first-order ephemeral streams, one to the east and the other to west of the crater, both tributaries of Purna River, flow towards the south. In the northern side of the lake, two more first-order streams – one flowing towards north and the other northeast – form tributaries of Penganga River.

Lonar Lake is the third largest natural salt-water lake in the world[20]. The near-circular lake of about 1 sq. km water-spread area (varies based on the climatic conditions) located about 135 m below the surrounding ground surface with steep wells all around (Figure 1 *b*). Maximum of six lava flows identified on the crater walls which dips the crater at about 10–15 degrees[11]. Twenty-two first-order streams originating from the outer rim converge into the lake, showing centripetal-type of drainage system. A feeder stream draining into the lake from the NE corner, originates in and around Lonar town. Though, presently there are no signatures of stream due to human interference and settlements, rainwater and part of the sewage water from Lonar town with a catchment area of about 0.2 sq. km drain into the lake. Total lake catchment area (including the lake area) is about 2.72 sq. km, which receives rainwater into the lake. A huge delta (~21.4 ha) was created in the northeastern portion of the lake due to stream discharge (only during the rainy days) and is being used for agricultural activity since a long time. The agricultural activity (mainly vegetables and fruits) is being carried out using the freshwater available in the delta region. The lake has no surficial outlet through which its water flows out directly.

Two perennial springs exist in the NNE of the crater at different levels from the ground surface. The spring close to ground surface is called Gomukh dhara and the other ~60 m below ground surface is called Sita-nahani (Figure 1 *a*). The discharge from the Gomukh dhara measured by the Groundwater Survey and Development Agency (GSDA; unpublished) during summer months of 2008 was ~2820 LPH (litres per hour). However, discharges from these springs vary according the season (more discharge during monsoon and less during summer). The discharge from the springs flows into the delta region and disappears. Another spring called Ramgaya located on the eastern side of the lake did not flow during the study period (2012–13). However, GSDA measured the discharge as ~500 LPH during the summer period of 2008. Apart from these three well-known springs, no other spring or groundwater seepage into the lake was reported, mainly during the summer months.

A unique feature of this lake water is its high alkalinity and salinity, and its specialized biodiversity. The lake periphery is covered with green algal material floating over the water. The water column in the lake varies from time to time, but has never dried fully in the past. The lake water is alkaline with pH ranging from 10 to 10.5. The alkalinity is a consequence of the high Na^+, low Mg^{2+} and Ca^{2+}. Sodium carbonate[3,21] was exploited from the lake water to manufacture soda in ancient times. The alkalinity of the lake water in terms of carbonates was reported to be 15.0%, 22.3% and 7.5%, and the salinity with respect to chloride 40.7%, 31.5% and 30.8% in the years 1910, 1958 and 1960 respectively[4]. Babar[20] compared the hydrochemical data of Choudhary and Handa[22] for the year 1970–71, and Muley and Babbar[23] for the year 1998, and found marginal difference between different parameters during the 28-year period. However, in recent times, lowering of alkalinity and salinity has been reported[24,25].

The rainfall measured adjacent to the lake by the irrigation Department from 1971 to 2012 (Figure 2) shows minimum (347 mm) during 1973 and maximum (1806 mm, extreme event) during 1998. Average annual rainfall for 42 yr is 759 mm with a standard deviation of 255 mm by removing the extremely high rainfall during 1998. Overall, rainfall distribution in different years shows either low or high rainfall occurs about 8–10 yr cycles.

GSDA has made detailed hydrogeological investigations around the crater, which revealed that like any basaltic region, groundwater potential zones are limited to weathered, jointed and fractured zones; and vesicular zones between the flows. Based on the groundwater level maps, GSDA has inferred that groundwater movement closely follows the surface topography. On the eastern and western sides of the Crater, the groundwater flow direction is towards south, whereas in the NE part (close to the Lonar village), it is inwards the crater. Figure 1 *b* shows a topographic cross-section across the Lonar Lake in the SW–NE direction covering the surface reservoir and Lonar town.

To understand the hydrological and hydrochemical dynamics of the Lonar Lake, water level was measured for about a year. Hydrochemical and stable isotope measurements were made on the lake water and surrounding groundwater at different times. Observed hydrochemical changes were compared with reference to lake levels. Hydrochemistry of lake water and the local groundwater was used to assess the effect of local groundwater on the lake level, if any. These data helped in understanding the long-term changes in the lake level and its hydrochemistry with reference to local rainfall.

Water samples were collected from the Lonar Lake four times (June and September 2012, February and May 2013) from different places. During May 2013, depth samples were collected using a local boat (float) across the lake to understand the hydrochemical stratification with depth, if any. Groundwater sampling was made within the crater floor, around the lake by making small pits and also from dug wells from the delta region during June 2012 and February 2013. Some rainwater samples

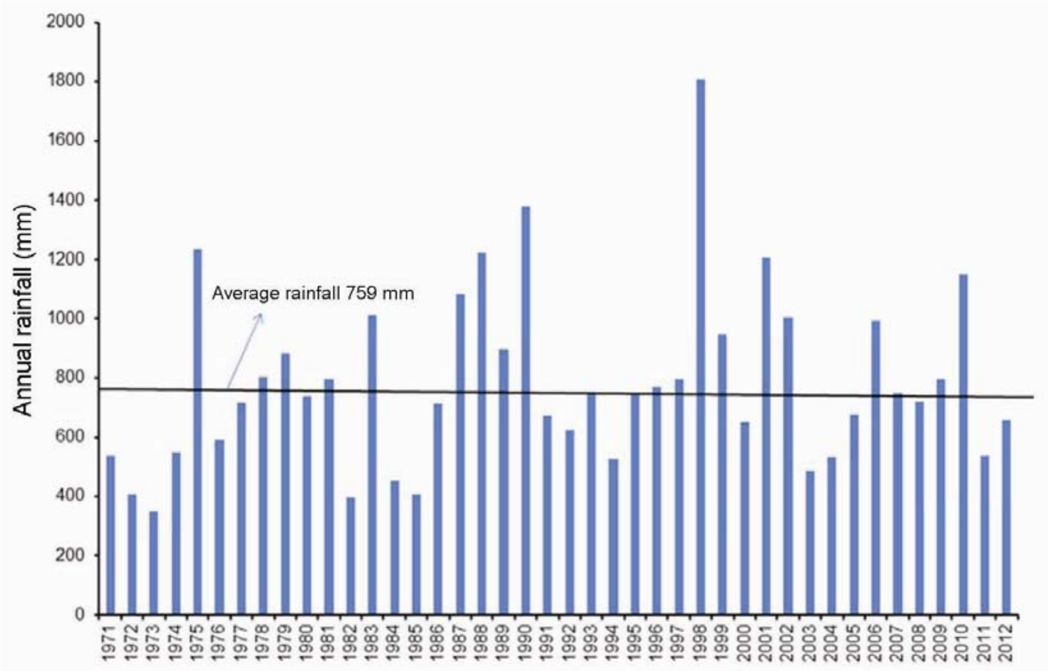

Figure 2. Forty-two years (1971–2012) rainfall history of Lonar area with an average of 759 mm.

were also collected from the lake area. All these samples were used for hydrochemical and stable isotopic measurements. Carbon-14 dating of two spring waters and also the Lonar Lake water was attempted. Lake water level was measured for about a year on hourly basis using a pressure sensor unit (the unit had failed for some time) to understand the changes in response to local rainfall.

The collected water samples were used to measure the major ion chemistry and stable isotope (oxygen-18 (δ^{18}O) and deuterium (δD)) values. pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured immediately after sampling. To measure EC and TDS, a higher-range electrode (Consort make SK23T, range 0.1–1000 mS/cm) was used. Other major anions and cations were measured in our laboratory at NGRI using Dionex ion-chromatographs (IC-90 and IC-2500) against the standards purchased from Merck, Germany. Anions were measured using the AS-14A Ion Pac, with 8 mM sodium carbonate and 1 mM bicarbonate as eluent and H_2SO_4 as regenerent with a mixed standard of F, Cl, NO_2, Br, NO_3 and SO_4 made in the required proportions. A CS-17 column was used for cation separation with 6 mM methane-sulphonic acid as eluent, and a mixed standard of Li, Na, K, Mg and Ca, in accordance with the approximate sample values. The samples with high TDS values (>600 mg/l) were diluted several fold according to the column specifications to measure both anions and cations. Measurements were made against the standards measured initially every day. Single standard checks were made in between the measurements and also at the end to ensure the data quality. Measurements have a precision of ± 5% of the total value. Majority of the analysed samples had ionic charge imbalances of ~5%. The δ^{18}O and δD in water samples were determined using Iso-prime stable isotope ratio mass spectrometer in our laboratory; values are reported relative to Vienna Standard Mean Ocean Water (VSMOW) with an uncertainty of ± 0.1‰ for δ^{18}O and ± 1‰ for δD. To measure the stable isotope content in waters, international standards (VSMOW, GISP and SLAP) supplied by the International Atomic Energy Agency (IAEA) were used to label the laboratory standards through plotting of three standards. Using the labelled laboratory standards, routine ^{18}O and D measurements were carried out. Carbon-14 activity was measured in two spring waters and one lake water using the low-level scintillation counters at NGRI, Hyderabad[27].

Figure 3 shows the measured Lonar Lake water level. Initially (when the water level monitoring unit was installed), the water column was 37.8 cm (reference point is arbitrary) on 14 June 2012. As the monsoon had already set in 9 cm rise in water level was observed in the lake due to 70 mm rainfall that occurred on 16 June 2012. Total rise in lake water level for the year 2012–13 was only 30 cm against the 615 mm rainfall during 100 days rainy period, whereas lake level dropped by 62 cm in 180 days (from 20 September 2012 to 10 April 2013) during post-monsoon. Based on the drop in lake level, average evaporation rate was estimated to be 0.3 cm/day, assuming no other way of water loss. However, during the summer months, it was about 0.5 cm/day. Total drop in lake level during the year (post-monsoon to pre-monsoon, last week of September 2012 to end of May 2013) could be

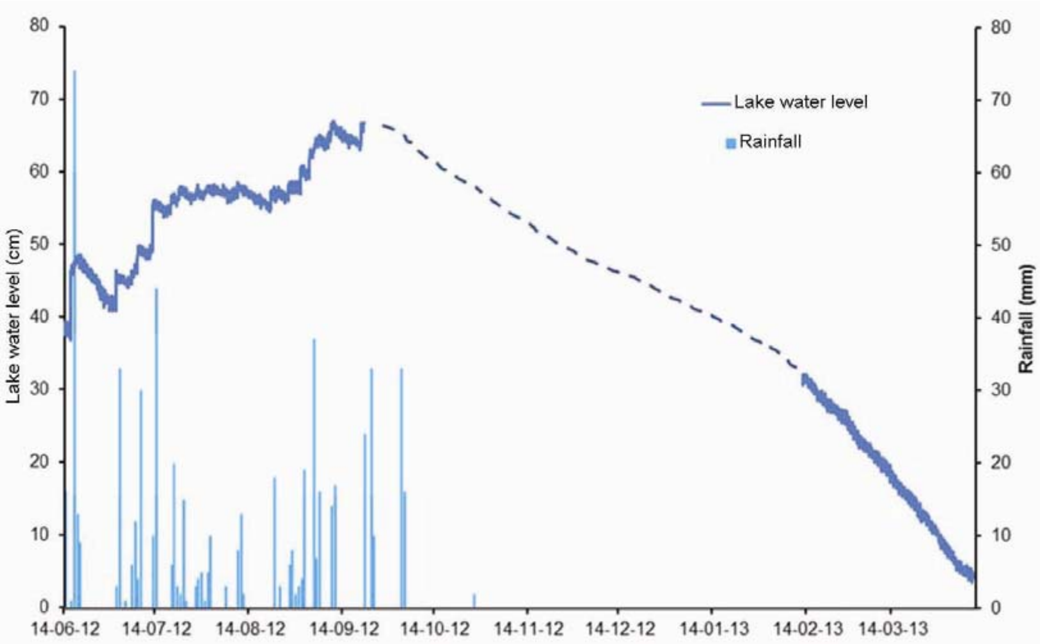

Figure 3. Hourly water-level measurement in the Lonar Lake during 14 June 2012 to 9 April 2013. The dashed line is interpolation based on available data, when the instrument did not work.

around 85 cm (interpolated with available data), when the rise was only 30 cm.

Table 1 shows the statistical distribution of different hydrochemical and stable isotopic parameters of lake water for different collections. The entire data are provided in Supplementary Table S1 (see online). Average ionic concentrations for different collections show marginal dilution for September 2012 sampling during rainy season. However there is no change in hydrochemical and isotopic values between in June 2012 and February 2013 collections. However, for the May 2013 collection, different ion concentrations are higher than the June 2012 sampling (except K, Mg and NO_3). pH of lake water is about 9.95 ± 0.05 for the first three collections, whereas for May 2013 collection, it is increased to 10.2 ± 0.1. Similarly, TDS values were $11,000 \pm 500$ mg//l for the first three collections and for May 2013 collection on an average it increases by ~500 mg/l. Among cations, sodium (~5500 mg/l) is several-fold higher than the others (Ca ~25 mg/l; Mg ~45 mg/l and K ~20 mg/l). Among anions, carbonate + bicarbonate concentration (~5500 mg/l) is more than the chloride concentration (~4800 mg/l), and sulphate concentration (~100 mg/l) is several-fold less. In general, F and Br concentrations are high in the lake water. For the first three collections, F and Br concentrations are about 5.5 and 23 mg/l respectively; these values are seen to increase to 6.2 and 27 mg/l respectively, in the May 2013 collection.

Average sodium, chloride and carbonate–bicarbonate values are slightly reduced in the September 2012 than the June 2012 collection. However, during May 2013 the respective ion concentrations increased more than the June 2012 concentration. As expected, very low (4 mg/l) NO_3 is observed in the June 2012 collection due to flood water; it is below detection limit (almost zero) in the May 2013 collection.

It has been reported that the alkalinity of the lake water is due to continuous accumulation of sodium carbonate resulting from disintegration of country rock and sodium chloride derived by strong monsoonal winds[3]. Chloride mass-balance made in small percolation tanks indicated increase in chloride concentration in the tank water four times over a period of three months due to evaporation[27,28]. The same principle can be applied for F, Cl and Br concentrations (the conservative ions) in this lake water.

The stable isotopes, $\delta^{18}O$ and δD, of lake water show only positive values ($\delta^{18}O$: 6.7 and 10.6‰ and δD: 30 and 50.1‰) for all the four samplings, whereas $\delta^{18}O$ and δD of rainwater range from –2.16 to +0.4‰ and –13.8 to +8.1‰ respectively. The plot of $\delta^{18}O$ and δD (Figure 4) shows clear groupings for the four sets of lake water samples. September 2012 data (post-monsoon) are slightly depleted in comparison to June sampling. This depletion is caused by addition of rainwater to the lake water. Among the four samplings, more positive values (+10.6‰ $\delta^{18}O$ and +50.1‰ δD) are registered by May 2013 sampling where lake levels dropped down by 55 cm in comparison with June 2012 sampling. A clear evaporation effect can be seen on lake water collected at different times in comparison to Global Meteoric Water Line (GMWL)[29] or local meteoric line (drawn based on local rainfall). Due to

Table 1. Statistical distribution of hydrochemical parameters 451 in Lonar lake water and surrounding freshwater during different seasons

	pH	Eh (mV)	Cond (μS/cm)	TDS	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_3	NO_3	F	Br	$\delta^{18}O$ (‰)	δD (‰)
				mg/l													
Lake water																	
June 2012 collection; no of samples = 20																	
Average	9.97	–178	19790	11240	5582	19	47	23	4891	117	1543	3676	4.0	5.3	23.7	9.03	37.80
Minimum	9.89	–207	18100	10200	5277	12	40	19	4558	103	1260	2320	0.0	4.2	14.2	7.80	35.88
Maximum	10.05	276	24200	13900	5905	108	61	34	5231	133	2060	4100	24.7	6.6	32.2	9.52	41.44
Standard deviation	0.05	107	1499	911	129	21	4	4	233	8	229	373	6.9	0.7	4.5	0.5	1.6
September 2012 collection; no. of samples = 6																	
Average	10.01	–214	18900	10683	5129	16	42	24	429	122	1170	3660	1.8	5.1	19.9	6.66	30.01
Minimum	10.00	–215	17400	9800	5026	13	41	21	4105	107	1030	3320	0.0	4.4	13.3	6.55	29.13
Maximum	10.06	–214	19700	11100	5224	24	44.0	28	4359	154	1480	3960	11.0	6.0	31.3	6.83	30.80
Standard deviation	0.02	0	802	462	73	4.0	1	3	98	19	163	209	4.5	0.6	7.3	0.1	0.6
February 2013 collection; no. of samples = 16																	
Average	9.92	–208	18844	10650	5586	40	44	22	4967	87	1479	3885	0.4	5.8	24.1	7.92	36.37
Minimum	9.84	–212	18400	10300	5137	13	41	19	4825	7	1160	2880	0.0	4.6	17.3	7.70	34.21
Maximum	10.01	–205	19200	10900	5839	126	52	26	5159	115	2206	4380	6.9	6.7	34.5	8.23	37.50
Standard deviation	0.06	2	210	151	298	36	3	2	106	34	343	357	1.7	0.7	4.4	0.1	1
May 2013 collection; no. of samples = 23																	
Average	10.22	–209	21035	11997	6247	15	43	29	5915	127	1637	4356	0.0	6.2	27.3	10.63	50.07
Minimum	10.06	–214	19500	11100	6018	13	39	24	5635	113	1420	3180	0.0	4.4	21.9	9.89	48.18
Maximum	10.31	–201	22000	12600	6596	26	46	36	6113	139	2260	4640	0.0	8.0	32.4	10.83	51.79
Standard deviation	0.08	4	699	426	136	3	2	3	113	6	219	319	0.0	0.8	3.1	0.20	1
Freshwater adjacent to lake																	
June 2012 collection; no. of samples = 7																	
Average	7.83	–83	1240	660	196	2.1	56	28	147	30.9	409	10	45	0.9	0.3	–0.59	–7.79
Minimum	7.60	–107	708	377	96	0.2	19	9	33	12.1	310	0	0	0.5	0.0	–2.64	–16.98
Maximum	8.27	–70	2120	1130	491	5.1	94	50	447	53.3	510	40	126	1.5	2.0	5.99	19.23
Standard deviation	0.28	16	475	254	134	1.7	32	15	140	15	75	17	57	0.4	0.8	3	13
February 2013 collection; no. of samples = 8																	
Average	7.74	–76	1067	571	165	1.9	49	33	95	18.8	435	14	24	0.9	0.0	–2	–12.00
Minimum	7.22	–95	600	319	90	0.4	27	20	19	5.0	325	0	0	0.5	0.0	–2.74	–16.69
Maximum	8.07	–46	2170	1170	513	8.0	84	50	307	43.8	738	60	115	1.3	0.0	–1.48	–7.79
Standard deviation	0.27	15	523	284	144	2.5	22	12	94	15.8	151	26	44	0.3	0.0	0.5	3

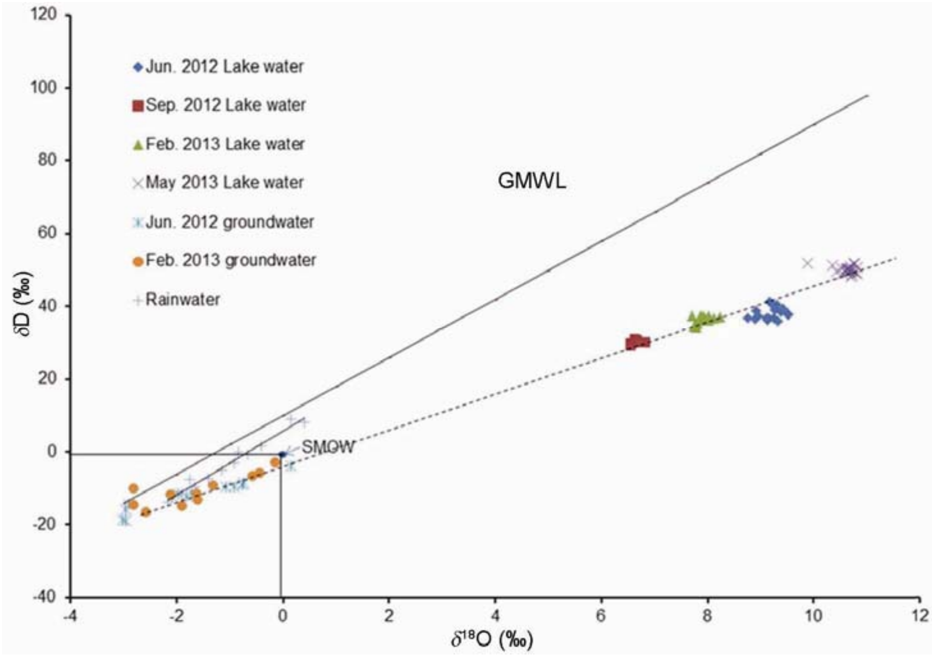

Figure 4. Stable isotope values of Lonar Lake water at different times, groundwater around the lake and the crater during pre- (June 2012) and post- (February 2013) monsoon collections and rainwater samples. Global meteoric water line (GMWL)[29] also shown for comparison.

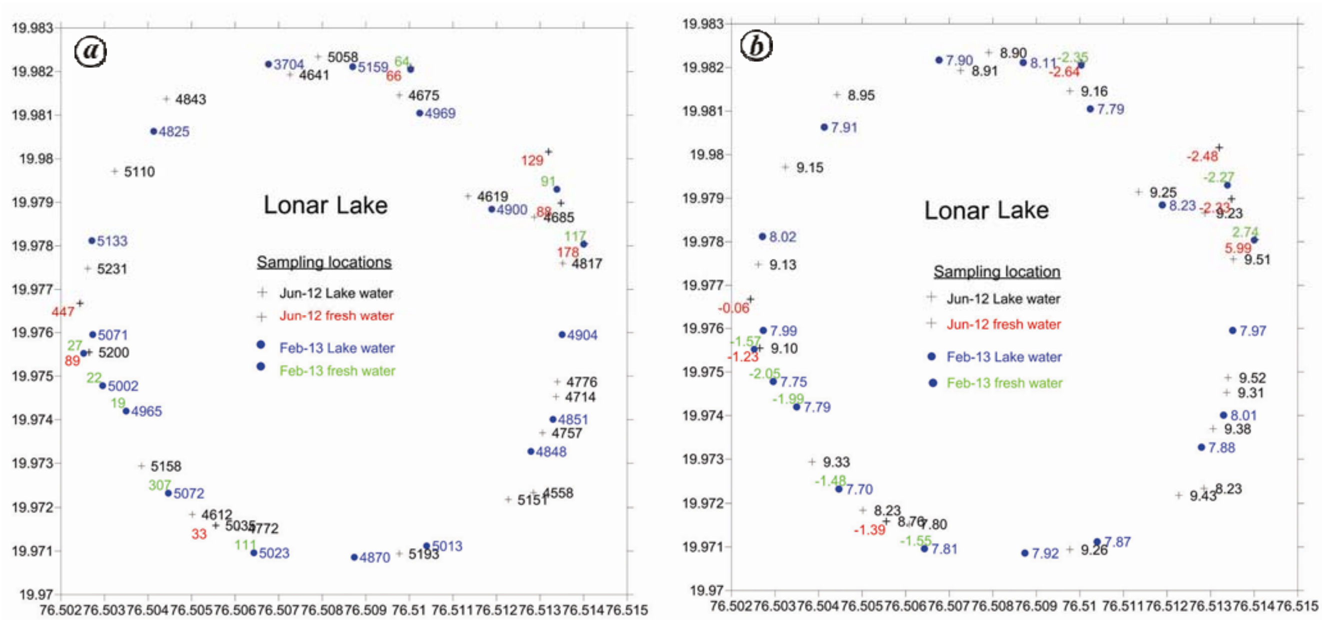

Figure 5. Spatial and temporal distribution of (***a***) chloride (mg/l) concentration and (***b***) δ^{18}O (‰) in lake water and surrounding groundwater (freshwater).

the evaporation process, isotopic gradient between the surface and bottom waters was reported for large lakes[30]; however, in the present case as the lake water column is less (~4 to 5 m) no such variation was observed.

Figure 5 *a* and *b* shows the spatial distribution of Cl^- and δ^{18}O of Lonar Lake water and surrounding groundwater. There is no spatial variation in hydrochemical or isotopic values (within the error limits) in different parts of the lake, but large variation is seen between the lake water and the surrounding groundwater. Similarly, between the two collections (June 2012 and February 2013) very marginal variation is seen in different parameters within the lake water as well as groundwater.

It is observed that the groundwater available around the lake within centimetres distance is fresh and potable. The TDS value of the lake water is ~11,000 mg/l, whereas for the surrounding groundwater, it is only ~600 mg/l (Table 1). Stable isotope values of lake water range between 7.8 and 9.4‰ for δ^{18}O; and 34 and 41‰ for δD, whereas for surrounding groundwater they range between –2.6 and –0.1‰ for δ^{18}O, and –17.0 and –4.0‰ for δD. Similarly, concentration of different chemical parameters are much lower in the surrounding groundwater than the lake water, except Ca, Mg and NO_3, which are generally more in freshwater.

Around the Lonar crater, groundwater is being exploited from the dug wells (domestic use) as well as through bore wells (agriculture purpose). Table 2 shows the hydrochemical data of groundwater for June 2012 and February 2013. In general, groundwater quality surrounding the crater is good (potable) and TDS values range from 300 to 400 mg/l (for the two collections). Sodium is the dominant cation and bicarbonate is the dominant anion in the groundwater. The stable isotope (δ^{18}O and δD) values of the groundwater, in general, are negative (δ^{18}O: –3.0 to –0.2‰ and δD: –18.9 to –3.1‰) for the two samplings and are close to the rainwater values.

Comparing the hydrochemistry of two spring waters collected four times, the Gomukh dhara spring is found to be more mineralized (TDS ~1000 mg/l) than the Sita-nahani spring (TDS ~500 mg/l; Table 2). In particular, NO_3 concentration in both the springs is quite high (~300 and ~80 mg/l respectively). Stable isotope values for Sita-nahani spring are relatively more depleted (δ^{18}O: –3.09 to –2.57‰ and δD: –18.47 to –16.72‰) than the Gomukh spring (δ^{18}O: –2.41 to –1.05‰ and δD: –16.06 to –8.63‰).

Radiocarbon measurements made on the two spring waters (Gomukh dhara and Sita-nahani) and the lake water showed 'Modern' (≤ 65 yr BP (before present with reference to 1950) age.

Though Lonar Lake is a unique feature, to assess the lake dynamics with reference to lake levels and hydrochemistry, no systematic data are available. Most of the available data are one-time measurements. GSDA (ref. 20) made detailed investigations for about six months (6 February 2008 to 9 September 2008) in and around the Lonar Lake during 2008. However, only one-time hydrochemical measurements without date of collection were reported. The GSDA study shows, a drop of ~73 cm in the lake water level during summer period (6 February 2008 to 21 July 2008) and the rise was only 26 cm (from 21 July 2008 to 9 September 2008) against 580 mm of rainfall. Water column in the lake was measured on 4 June 2008 to be 6.8 m. The reported drop or rise in lake water levels are of short duration rather than the yearly changes. According to the 2007 data, rainfall in this area stopped during the last week of September 2007 and the measurements started from 6 February 2008. Hence there are no data for the initial four months of dry period. Therefore, the lake water level drop should be more than 73 cm between post- and pre-monsoon. Similarly, the lake water level measurement had stopped on 9 September 2008, whereas the rains continued up to second week of October and another 200 mm rainfall occurred during that one month period. The lake water level should have been measured at the end of the second week of October 2008 to get the total rise in level. Hence, the rise in the lake water level could be more than the reported value. However, the lake water level drop could be certainly more than rise during the year 2008–09. Though GSDA made a good attempt on seasonal variation of lake water levels, it has not studied the hydrochemical changes.

During the present study period, the lake water level rose only 30 cm, against 615 mm rainfall during the monsoon (14 June 2012 to 20 September 2012) and the drop (post to pre-monsoon) was about 85 cm. Though there was only 19% deficit in rainfall (with respect to annual average), lake water level dropped by 55 cm (with reference to initial values). During 2011–12, total rainfall was only 538 mm (about 30% less than the average rainfall) and during 2010–11, it was 1151 mm (much higher than the annual average). Though lake water levels were not available for the years 2010–11 and 2011–12, considering that the principal source of water inflow into the lake is only through rainfall, it can be assessed that in the post-monsoon period of 2010–11, water level in the lake might have been relatively higher. Though during 2011–12, rainfall was less by 30%, effect on the lake level was not seen due to high rainfall in the previous year and the effect was clearly seen during 2012–13 even though rainfall was only 19% less. Hence, it is clear that consecutive droughts or high rainfall conditions control the lake water level.

The hydrochemical and stable isotopic measurements made during the study show that basically there is a marginal change due to dilution between pre- and post-monsoon values (June and September 2012). This can be expected as the increase in water level from pre- to post-monsoon is only 30 cm. Considering the average water column in the lake ~4 m (measured during May 2014 at a few points), and increase in water level is 30 cm due to local rainfall during 2012–13, about 7.5% dilution should take place. The hydrochemical values of June and September 2012 samplings have also shown similar dilution as that calculated. Increase in chemical values (Na, Cl, Br) and enriched δ^{18}O and δD during May 2013 is solely based on the evaporation process in the lake, in turn supported by reduction in lake water level.

A minor variation in different hydrochemical values found in the Lonar Lake water collected at different locations is within the error limits presented in Figure 5 *a* and *b*. In contrast to the lake water, the groundwater that exists just adjacent to the lake water boundary (within centimetres distance) is freshwater (Table 1). Another interesting observation is that there is no broad transition zone between the highly saline lake water fresh groundwater. This could be due to the black sticky clay

Table 2. Statistical distribution of hydrochemical parameters in groundwater around Lonar crator and spring waters

	pH	Eh (mV)	Cond (μS/cm)	TDS	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_3	NO_3	F	Br	$\delta^{18}O$ (‰)	δD (‰)
				-----mg/l-----													
Groundwater																	
June 2012 collection; no. of samples = 13																	
Average	7.89	–86	796	421	95	0.9	25	47	100	50	254	8	24	2.1	0.9	–1.75	–11.91
Minimum	7.34	–146	500	266	20	0.4	0	11	25	10	40	0	1	0.2	0.6	–3.02	–18.86
Maximum	8.96	–54	1430	760	269	2.0	52	73	303	109	412	33	56	6.1	1.4	–0.15	–3.70
Standard deviation	0.50	28	240	126	72	0.4	20	23	87	33	121	12	20	2	0.3	1	4.2
February 2013 collection; no. of samples = 10																	
Average	7.75	–76	642	342	63	0.6	30.3	48.0	47	29	300	5	27	1.9	0.6	–1.52	–10.0
Minimum	7.24	–131	509	273	21	0.4	0.1	8.5	6	5	52	0	0	0.4	0.5	–2.81	–15.0
Maximum	8.71	–47	970	500	184	0.9	50.2	85.0	212	98	454	33	74	6.6	0.8	–0.14	–3.11
Standard deviation	0.51	29	130	64	53	0.2	17.6	23.4	64	28	137	11	24	2.3	0.2	1	4.2
Gomuk dhara (spring)																	
11-06-12	7.23	–49	2440	1300	185	6.1	144	65	356	90	463	0	414	0.0	n.a.	–1.05	–9.06
21-09-12	7.13	–49	1540	820	121	3.4	84	121	165	51	368	0	183	0.5	n.a.	–2.41	–16.06
12-02-13	7.36	–55	1800	940	126	5.2	104	141	224	56	438	0	219	0.6	n.a.	–1.61	–11.56
07-05-13	6.91	–36	2210	1180	165	6.0	128	173	309	76	490	0	318	0.0	n.a.	–1.29	–8.6
Sita nahani (spring)																	
12-06-12	7.96	–88	828	440	63	0.7	53	52	53	23	315	0	70	0.4	n.a.	–3.09	–18.47
21-09-12	7.27	–56	970	520	67	0.9	54	43	65	25	320	0	75	0.5	0.56	–2.66	–18.26
12-02-13	7.45	–59	920	495	72	1.0	62	65	85	29	315	0	96	0.4	n.a.	–2.57	–16.72
06-05-13	7.29	–56	940	500	72	0.8	57	61	72	27	323	0	81	0.4	n.a.	–2.75	–17.90

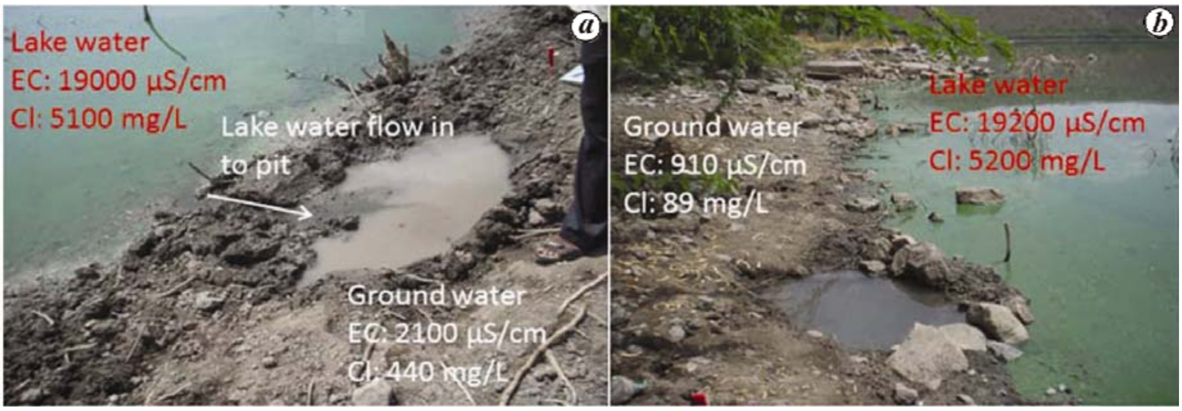

Figure 6. Highly saline Lonar Lake water and adjacent (within centimeters distance) fresh water without any transition zone. (***a***) Lake water level slightly more than the adjacent groundwater (June 2012, pre-monsoon). (***b***) Both levels almost equal (September 2012 post-monsoon).

Table 3. Carbon-14 ages of lake and spring waters

Sample	pMC	Age
Lake water	100%	Modern
Gomukh dhara (spring)	100%	Modern
Sita nahani (spring)	100%	Modern

pMC, Percentage modern carbon.

(impervious) spread in the entire lake bottom, which does not allow any migration or interaction between these two chemically different waters. The fresh groundwater available at the margins of the lake is nothing but rainwater that has entered in the colluvium during rainy season. Once the colluvium has saturated, the rain water flows over the ground surface and enters in to the lake. Further, it was also observed that during June 2012, the level of adjacent groundwater was slightly lower than the lake water level; however, the groundwater was fresh (Figure 6 *a*). As expected, in the February 2013 (post-monsoon), it was observed that the groundwater around the lake was few millimeters higher than the lake water level (Figure 6 *b*). Even though local groundwater table around the crater is much higher than the lake level, quaquaversal dip of basaltic flows around the lake in association with compactness of the flows not allowing any groundwater seepage into the lake, except in the NNE and a portion of east where springs exist. No seepage of groundwater was seen from the crater walls into the lake during non-rainy period, except two springs. High NO_3 content, depleted stable isotope values and Modern carbon-14 ages of two spring waters indicate these are normal groundwater from the surrounding areas discharging in the form of springs where suitable geological structures exist. These spring waters percolating down at delta region are an additional source of freshwater, being used for agriculture. Hence the spring discharge may have marginal influence on the lake water level, which is spread over 1 km^2. A recent study by Komatsu *et al.*[31] showed that the lake water level appears to be influenced by surface run-off during rainy season and ground water input effective during both the rainy and dry seasons. The present study shows that though the lake is influenced by surface water (rainfall) during the rainy season, no influence of groundwater or spring water on lake levels is observed during the dry period.

Based on few earlier scientific report, it is considered that Lonar Lake levels are being increased, while the alkalinity and salinity is decreased. This claim is based on the comparison between the older hydrochemical data[3,4,21] and a few recent measurements. However, these studies have not considered the lake water levels of the respective periods. According to the records[4], lake water level increased from 1.8 m during 1953 to 5.4 m during 1960. Water level in the lake was reported to be less during 1985 and a great extent of the lake basin got exposed along with encrustation of the salt[15]. Later the water level increased between 1991 and 1992 (ref. 15). GSDA correlated the low lake water level with low rainfall between 1975 and 1985. GSDA measured the lake water column on 4 June 2008 to be 6.8 m.

In the present study, water column was measured on 7 May 2013 across the lake in two traverses; the maximum water column was found to be 4.25 m at several locations. This shows that the lake water level had reduced from the year 2008 to 2013. Further it also conforms with increased chloride concentration from ~4300 mg/l[21] to ~5000 mg/l (present measurements). Hence, the variation in hydrochemistry (Na, Cl, Br, etc.) and stable isotope values is found to be in proportion to the lake water level.

Hence, based on the local geological conditions, field investigations and groundwater flow directions around the crater, it can be concluded that the groundwater movement is away from the crater and there is no other input source to the lake, except local rainfall and two perennial springs, one or two seasonal springs and a part of drainage from Lonar town. Thus, the lake hydrology is totally controlled by local rainfall, while its chemistry is controlled by local rainfall and evaporation.

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