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An Assessment of Inter-Seasonal Surface Water Level Fluctuation of Lonar Crater Lake, Maharashtra, India Using Multi-Temporal Satellite Dataset

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Abstract: Lonar Crater Lake in the Buddana district of Maharastra state, India is the third largest natural salt water lake in the world. It is mysterious due to its unsolved & unique limnology and ecological biodiversity. It occupies the geographical position of 19°58' N & 76°31' E. The crater has a diameter of 1.8 km (rim to rim) with an average depth of 137m while the inside lake diameter is of approximately 1.2 km in average. The Lake surface area changes seasonally. The USGS Landsat dataset of 30m spatial resolution has been used to map the lake surface area seasonally for the years: 2009, 2010, 2011, 2015, 2016 and 2017 respectively. The average slope of the Lonar Crater (assuming frustum of cone) has been calculated as 19°. The results have shown a huge reduction in the lake volume in the summer 2017 resulting in the maximum declination of Lake water level (~11 m). While there is just a little increment in the lake volume in monsoon 2017 resulting in the minimum inclination of Lake water level (< 1m). The rate of removal of water from the lake is observed faster than the rate of filling the lake with water, in the recent years (2015-2017). Such type of study will enhance the potential area of remote sensing technology up to a larger extent. Also the study will help us to understand the behavior of large Lakes/water bodies. Proper and regular monitoring of such water bodies may lead to know their exact conditions in this changing climate in order to save the precious water resources.

Keywords: Remote Sensing, NDWI, Lonar Lake, Water level, Volume, Climate

1. Introduction

Around 50000 years back a massive meteorite struck the earth's surface having a range of 60m long and weighted around 20 lakh tones with a velocity of 25km/sec [14], [13]. That collision resulted in the formation of a crater named 'Lonar', located in the Buldhana district of Maharashtra, India. It is the only hypervelocity meteoritic impact crater in basalt rock [14]. It is hydro-logically active and the third largest natural salt water lake in the world [17]. It is the only lake of its own kind in Asia, occupying the geographical position of 19°58' N & 76°31' E. It is mysterious due to its unsolved & unique limnology and ecological biodiversity. Due to its uniqueness in terms of its salinity, alkalinity and biodiversity, it always remains an interesting and attractive research subject for the chemical and biological scientists and researchers. Several studies revealed its salinity [8], [2], its pH [14], its temperature [12] and its water phytoplankton [16], [11]. Regarding its geology, most early visiting researchers suggested a volcanic origin for the crater and signified its location within a thick pile of basaltic volcanic rocks [10], [1], and [6]. They argued that the Deccan basalts themselves erupted from Lonar Crater [9].

Though it is not a new subject to research, a very few research work has done of its hydrology and the dynamics of its water level. Earlier studies have suggested that the depth from the rim crest to the crater floor was 230-245m with circulatory index of 0.9 [3], [2]. But later on the recent studies have shown that the simple, bowl-shaped crater has a present-day average rim to rim diameter of 1.88 km and an average rim height of 30 m with an average crater depth of 137m [7], [14] and [5]. In contrast to the rim-to-rim diameter, the inside lake diameter is of approximately 1.2 km in average [5]. Due to its 'bowl' or 'frustum of cone' shape and surrounded by ejecta blanket, there is no such any outlet to release or move out the water from the lake [17]. But, the recent studies have suggested that the lake level within Lonar crater appears is influenced by surface runoff that is active during the monsoon season and groundwater input that may effective during both the rainy and the dry seasons [5]. Because of the lake level fluctuation is linked to the monsoon climate, it is reasonable to assume that precipitation in the catchment area including the Lake surface and evaporation from the lake are the two main driving factors which controls the lake level fluctuation under today's climatic condition [5].

Till now, not a single study has done on the dynamics of the Lonar lake surface water level fluctuation. Though it is well understood that the lake surface water level witnesses fluctuation due to addition of water in monsoon season as rainfall, and removal of water in summer season as surface evaporation, which leads to the change in Lake's diameter seasonally. It is not yet commented anywhere on the quantitative measurements of the lake level fluctuation i.e, (i) By how much quantity the surface water level of Lonar Crater Lake is fluctuating from MSL, and (ii) What is the volumetric change of Lake in terms of addition (rainfall) and removal (evaporation) of water. In addition to that, the use of new and advanced space technologies such as satellite remote sensing & GIS technology is far away for such study, which is rapidly emerging as a reliable tool for the assessment of our natural resources in this changing climate. Therefore, the study is largely focused on the advanced remote sensing techniques to estimate the seasonal (pre-monsoon and post-monsoon) fluctuation in the lake surface water level, and volumetric change of Lonar Lake for different years of 2009, 2010, 2011, 2015, 2016 and 2017 respectively. A block model diagram of Crater impact Lonar Lake has shown below in "Figure 1" to give a brief description about the structure of the lake such type of study will enhance the potential area of remote sensing technology up to a larger extent.

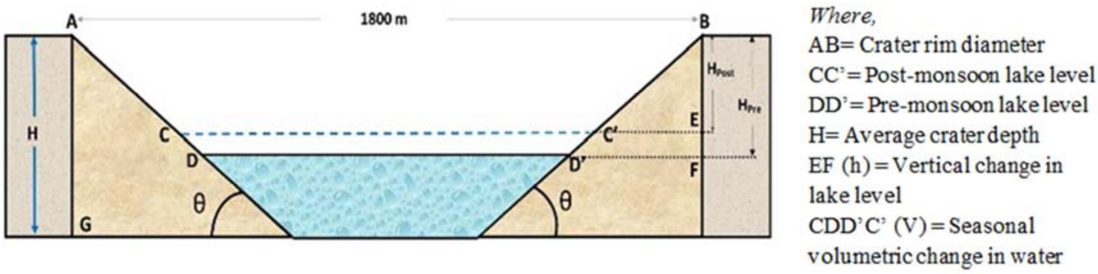


Figure 1. *Block model diagram of Lonar Crater Lake.*

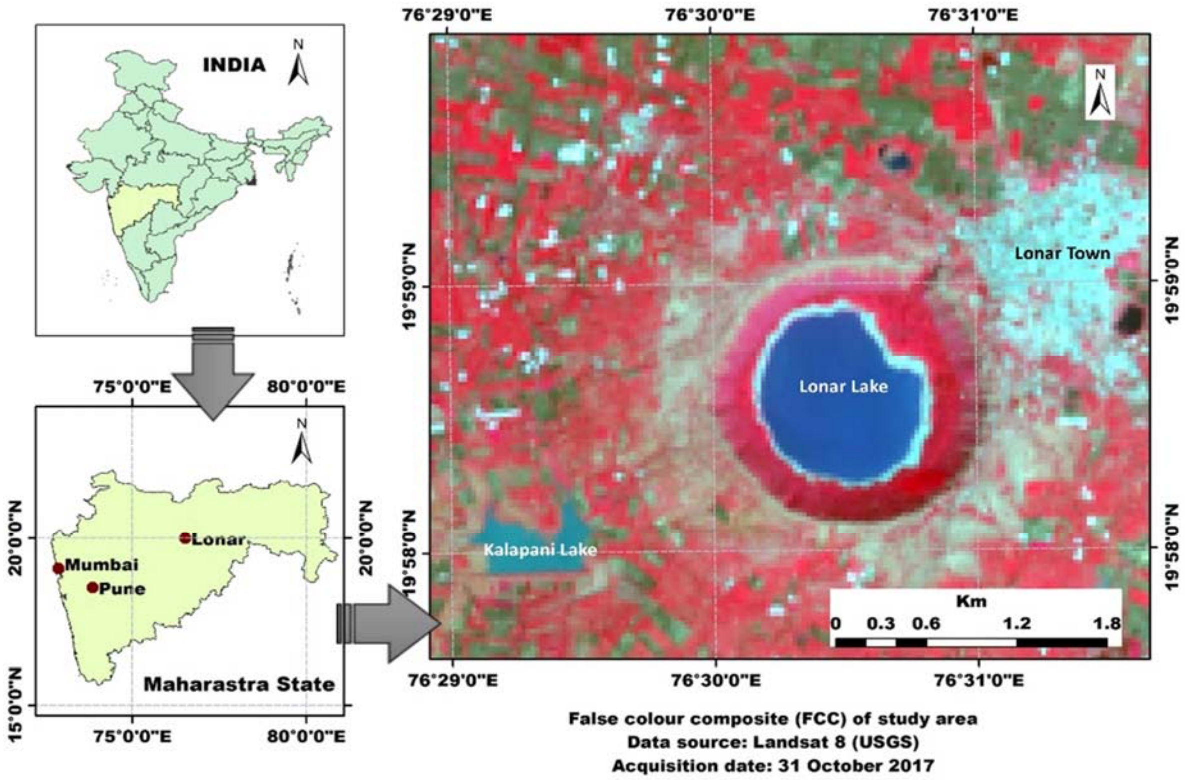


Figure 2. *Location map of study area.*

2. Study Area

The study area Lonar crater is situated near to Lonar town in Buldhana District of Maharashtra, India is shown in "Figure 2". Its geographical position 19°58' N & 76°31' E. Lonar is 376 km away from Pune city. The climate is tropical Savana climate. The average annual rainfall nearby Lonar is 752 mm. Rainfall occurs during July to September. Temperature ranges from 20°C to 34°C in winter and summer respectively. The hottest month lasting from March to June. The uniqueness of Lonar Crater is alkalinity and salinity, which reaches its highest limit in summer. Its average alkalinity varies from pH 9.5 – 10.0 [14]. There is one perianal stream enters in the crater at North-Eastern side called as *Dhar* Stream.

Data Used

Pre-monsoon (May) and Post-monsoon (Oct-Nov) season's dataset has been used for the present study. All the dataset are acquired by the USGS Landsat satellite series for the desired years i.e. Landsat-5 TM for years 2009, 2010 and 2011 & Landsat-8 OLI for 2015, 2016 and 2017(*Source:* http://www.earthexplorer.usgs.gov/). Both the satellite sensors are of 30m spatial resolution. Google Earth (DigitalGlobe) elevation data has been used for the calculation of average slope of the crater "Figure 3", and for determining the reference lake water level "Figure 4".

3. Methodology

The pre-monsoon and post-monsoon dataset has acquired in order to perform the digital Normalized Difference Water Index (NDWI) classification technique. The NDWI has been performed by considering the GREEN and NIR bands of the Landsat dataset, i.e. band number 2 and 4 for LANDSAT-5 TM and band number 3 and 5 for LANDSAT-8 OLI. The NDWI is used to monitor the changes related to water content in water bodies, using green (0.5-0.6 µm) and (Near Infrared) NIR (0.7-0.9 µm) wavelengths, defined by Geo et.al in 1996 [4].

$$\text{NDWI} = \frac{Green-NIR}{Green+NIR} \tag{1}$$

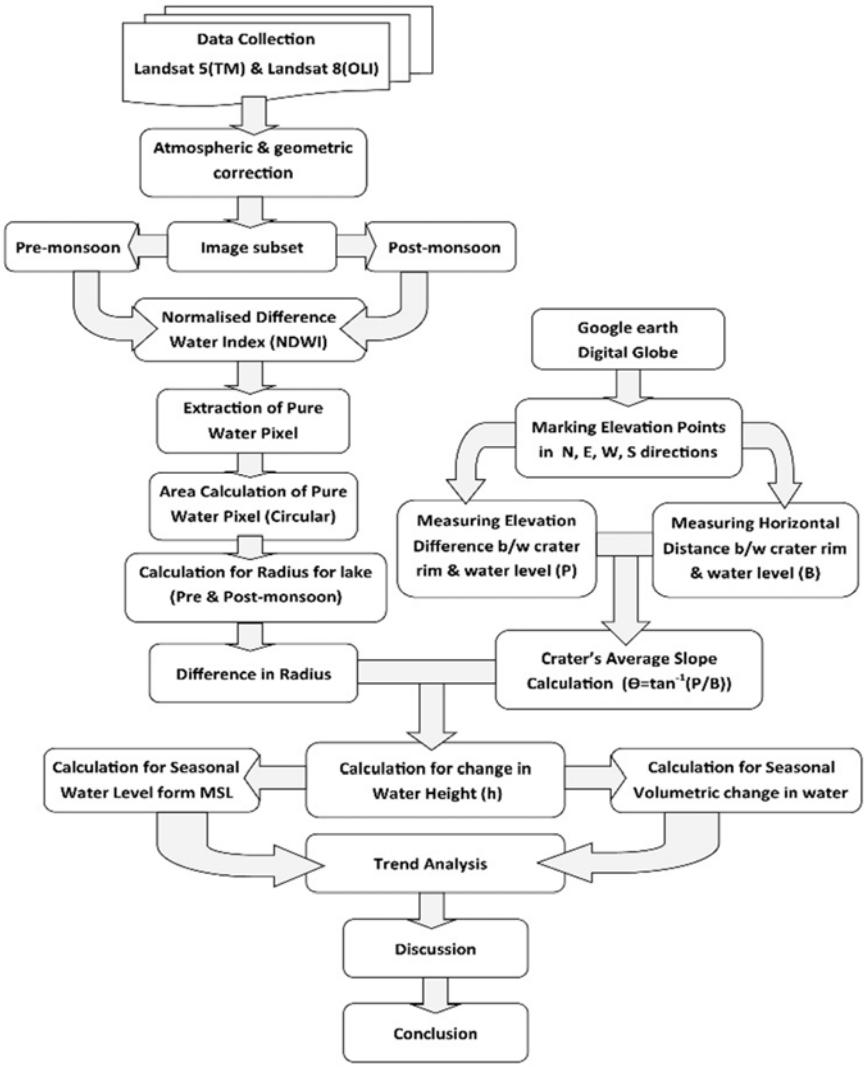


Figure 3. *Methodology Flowchart.*

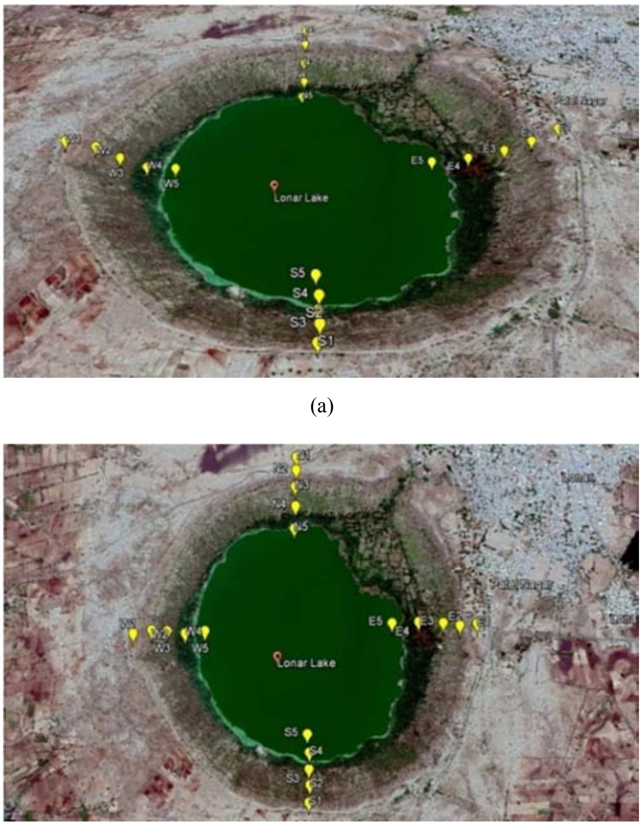
The following is the general work flowchart of the study:

On the other hand the Google Earth *DigitalGlobe* high resolution elevation data has been used to mark the points on the crater in all four directions i.e. East (E), West (W), North (N) and South (S) along the crater slope "Figure 3" and "Figure 4".

From Figure "1", Using Trigonometric ratio in Δ BFD', having $\angle BFD' = 90°$.

$$\tan \Theta_i = \frac{FD'}{BF} \quad (2)$$

Where, *tanΘ* is defined by the slope of the Lonar crater and *Θ* is the angle of slope. Such that, FD' is the average horizontal distance between the maximum elevation (i.e. E1, W1, N1 and S1) and lake water level (i.e. E5, W5, N5 and S5) for each Θ_i, respectively. Similarly, BF is the average elevation difference between the above corresponding points for each Θ_i.



(a)

(b)

Figure 4. *Marked sample point on Lonar Lake, 5 points on each direction; Google Earth Image (Image©2017, DigitalGlobe) (a) Oblique view, (b) Nadir view*

From the NDWI algorithm "(1)", an approximate surface area of the lake has been calculated for each particular seasons by multiplying the number of pure water pixel (Count of DN values) with the spatial resolution of the satellite data (30m in this study).

$$\text{Surface Area of Lake (S)= Number of pure water pixel} * (30\text{ m})^2 \quad (3)$$

After calculating the lake surface area, the radius of the lake has been estimated for each individual seasons. Here, the surface area of the lake is assumed to be circular (actual circulatory index of lake is 0.9, which is 1.0 for an ideal circle).

$$\text{Radius of lake (R)} = \sqrt{S/\pi} \quad (4)$$

(Value of $\boldsymbol{\pi}$ is taken as 3.14)

Similar to Equation "(2)", by applying the Trigonometric ratio in Δ XYZ',

Having $\angle XZY = 90°$

It will have,

Base = R_{post} - R_{pre}

Slope = 19° (Calculated)

Vertical change in the seasonal water depth (h) can be calculated as,

h = tan19° * (R_{post} - R_{pre})

$$\text{OR, } h = 0.34 * (R_{post} - R_{pre}) \quad (5)$$

(NOTE: R_{post} is the radius of grater circular lake, and R_{pre} is the radius of smaller circular lake, satisfying the formation of an ideal frustum of cone "Figure 5").

Now, the final task, i.e. to calculate the seasonal volumetric change of the lake is calculated using the volume estimation method of the Frustum of Cone [15], "Figure 5".

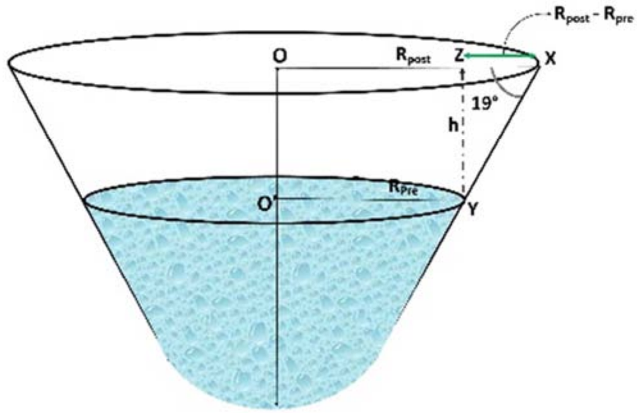


Figure 5. *Model diagram of Lake as a Frustum of Cone.*

Where,
Rpost = Radius of lake when water level is high
Rpre = Radius of lake when water level is low
h = Height of water fluctuation in the lake

Change in the volume of lake= Volume of Frustum of cone=

$$\frac{\pi}{3} * h * [(R_{post})^2 + (R_{pre})^2 + (R_{post} * R_{pre})] \quad (6)$$

4. Result and Discussion

4.1. Normalised Difference Vegetation Index (NDWI)

Equation "(1)", the Normalised Difference Water Index (NDWI) has been performed for the all the chosen seasons of the desired years. The digital classification of the NDWI layer has been classified in three classes. The classification has done under the '*Natural Break*' classification approach, as it gives best results under. The NDWI layer has digitally classified as: (i) pure water pixel (ii) Non-water pixel and (iii) partially saturated wet soil pixel, as the three identical classes on the basis of the DN values. The pure water pixel (class-1) has extracted out from the NDWI classified layer and the map layout has been created "Figure 6". The pre monsoon and post monsoon layers have kept one over another in order to see the change in the lake surface area coverage for all the desired years. It has been found that the lake surface area during the pre-monsoon season (i.e. summer season) remains lower than the lake surface area during post-monsoon season (i.e. end of rainy season). It is clearly visible by comparing all the layers that, the rate of filling lake by water in rainy season is lower than the rate of evaporation from the lake in summer season (especially noticeable in the year 2017). In order to get a quantitative values of these change the following tasks has been performed.

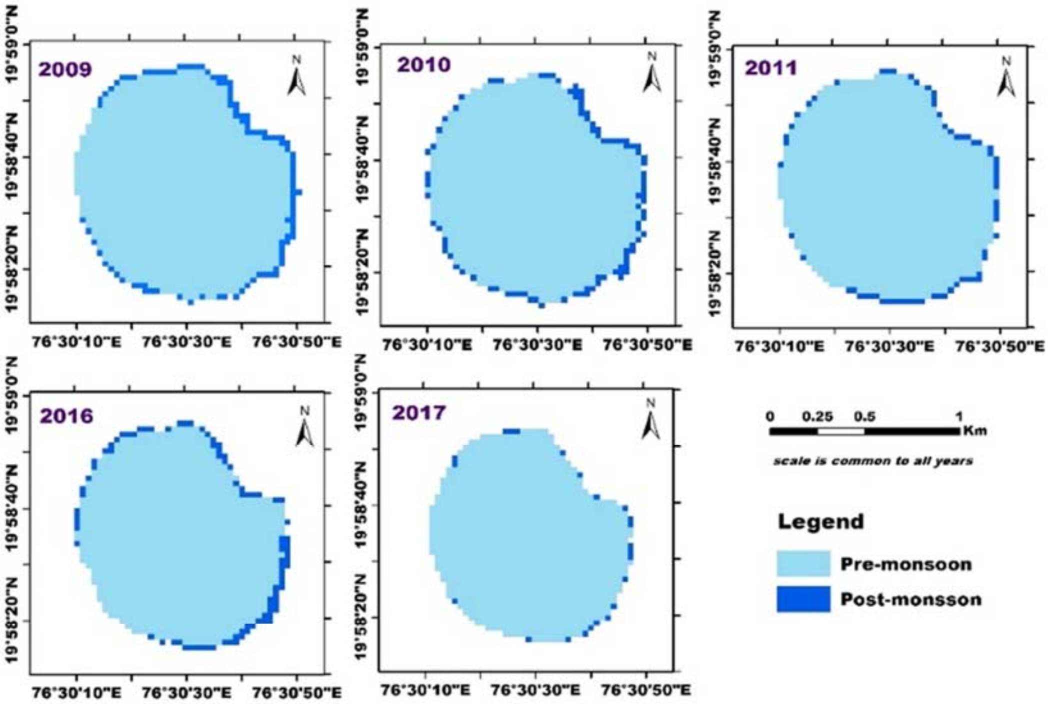


Figure 6. *Seasonal change in the surface area of Lonar Lake for various years.*

4.2. Seasonal Lake Radius (R)

Table 1. *Lonar Lake surface area and radius for the considered seasons (date).*

Date	Lake Surface Area (m^2)	Radius of lake (m)
11_may_2009	1048376	578
25_oct_2009	1092043	590
14_may_2010	1037560	575
29_nov_2010	1123370	598
17_may_2011	1088998	589
24_oct_2011	1148240	605
04_nov_2015	1064700	582
14_may_2016	983700	560
28_oct_2016	1057500	580
24_may_2017	941400	547
31_oct_2017	946800	549

In order to calculate the seasonal lake radius, first the pure water pixels has been counted and the total surface area of the lake has been calculated using "(3)" for all the different seasons. After that, it is assumed that the lake surface has a circular shape. And finally the radii of the corresponding lake surface areas has been calculated using "(4)". It has been found that the Lonar Lake has reached its maximum diameter (i.e. maximum water content) in the post-monsoon season of year 2011, which was 1210 meter in diameter. The pre-monsoon season of year 2010 and 2011 are observed as good water quantity in the lake, "Table 1". This was basically due to the effect of La-Nina event as both the years have witnessed above normal rainfall during the monsoon seasons. On the other hand, the scenario is totally different for the year 2016 and 2017, as both the years have witnessed below normal rainfall during the monsoon period due to El-Nino effect, resulting in the reduction of the lake diameter hence less water content.

4.3. Lonar Crater Average Slope (Θ)

From the "Figure 4", the Horizontal and Vertical differences between the Crater rim and the surface of the lake has been estimated in order to calculate the average slope of the Lonar Lake. It has been found that the Eastern side of the lake has the least slope gradient (15.6°) whereas the Southern side of the lake has the maximum slope gradient (~23°), "Table 2". All the four faces slopes are averaged to get the average slope for the Lonar Crater whose value assumed to be constant throughout the years (i.e. no change in the average slope gradient). The average slope (*tanΘ)* of the crater is calculated around 19° using "(2)".

Table 2. *Lonar Crater directional and average slope statistics.*

Direction	Elevation	Horizontal distance between rim & lake Surface (m)	Slope (tanϴ)	Average Slope
E1	589			
E2	549			
E3	509	380	15.6°	
E4	490			
E5	483			
W1	581			
W2	558			
W3	517	330	16.7°	
W4	494			
W5	482			19°
N1	587			
N2	548			
N3	505	285	20.3°	
N4	488			
N5	482			
S1	593			
S2	553			
S3	508	260	23.2°	
S4	488			
S5	482			

4.4. Seasonal Lake Water level Fluctuation (h) and Corresponding Change in Volume (V)

The difference in the radii (R_{post} - R_{pre}) of the lake surface (NDWI Class-1), gave the information about the horizontal change or shifting of the lake boundary "(Section 5.1 & 5.2)". From "(Section 5.3)", the average slope information has extracted. The reference water level has considered as 482.25m in the summer 2017 (*Google Earth DigitalGlobe Elevation data*).

Table 3. *Lonar Lake estimated lake level for different seasons.*

Date	Estimated Lake water level (m)	Estimated change in water level (m)
11_may_2009	492.79	
		4.08
25_oct_2009	496.87	
		-5.10
14_may_2010	491.77	
		7.82
29_nov_2010	499.59	
		-3.06
17_may_2011	496.53	
		5.44
24_oct_2011	501.97	
		-7.82
04_nov_2015	494.15	
		-7.48
14_may_2016	486.67	
		6.80
28_oct_2016	493.47	
		-11.22
24_may_2017	482.25	
		0.68
31_oct_2017	482.93	

Komatsu, G. et al. in 2014 [5] have also found through their ground verification that the water level remains around 480m to 485m in the summer, which quite satisfies the considerations taken into the study, "Table 3". Finally using "(5)", the seasonal change or fluctuation in the vertical water level (h) has been calculated. Results have shown that there is a declining trend in the lake water level (from MSL) for the same season of the different years. This indicated that the recent summer months are evaporating more and more water from the lake resulting in the lowering of Lake water level. The water level has reduces by ~10 m for the same pre monsoon season since 2009. The similar trend has been observed for the post monsoon or rainy season. It indicates that the addition of water through rainfall has reduced in the recent years as compared to the past years. In this case the water level has reduces by ~15 m in the same post monsoon season since 2009, see "Figure 7". This may be due to the rise in global surface temperature due to climate change which resulted in the less rainfall and more evaporation (i.e. a net reduction in the lake volume).

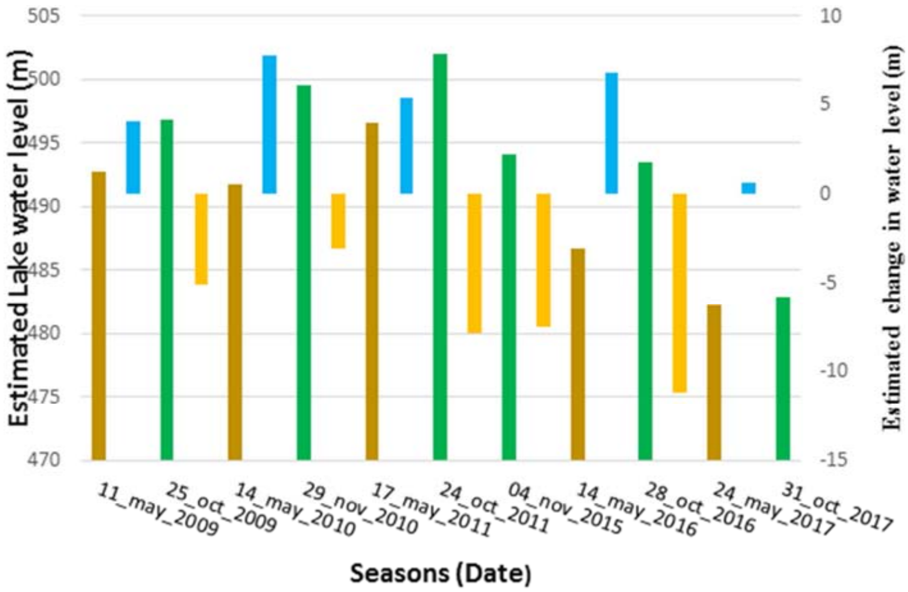


Figure 7. *Seasonal lake water level (m), Pre-monsoon level (Brown), Post-monsoon level (Green); & change in water height (m), Increasing (Blue), Decreasing (Yellow).*

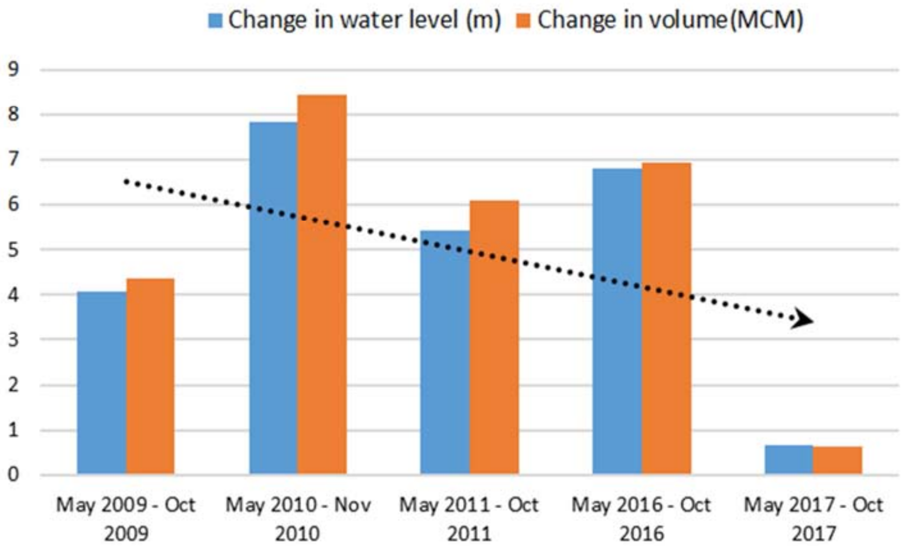


Figure 8. *Trend of addition of water into the lake during monsoon season.*

Once the change in the water level (h) has been calculated, it was quite simple to estimate the change in the volume of lake from a peak rainy season to a peak summer. The change in volume is calculated using the volume estimation method of the Frustum of Cone "(6)". The results have shown a huge reduction in the lake volume in the summer 2017 resulting in the maximum declination of Lake water level (~11 m), followed by summer 2016. While there is just a little increment in the lake volume in monsoon 2017 resulting in the minimum inclination of Lake water level (< 1m), followed by monsoon 2009. The volume information has mentioned in the following "Table 4".

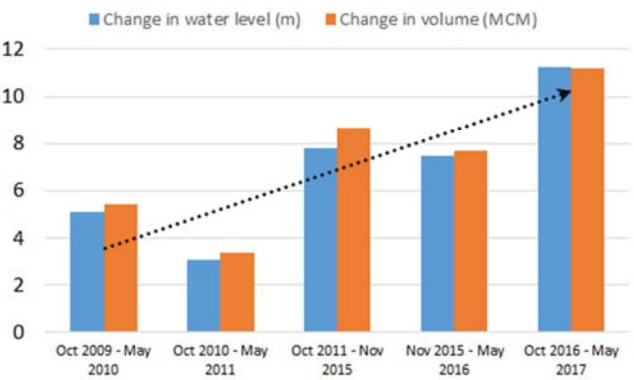


Figure 9. *Trend of removal of water from the lake during summer season.*

Table 4. *Lonar Lake estimated change in volume (in Million Cubic Meter; MCM) for different intervals.*

Interval	Change in water height (m)	Nature of Change	Change in Volume (MCM)
May 2009 - Oct 2009	4.08	Increasing	4.3717
Oct 2009 - May 2010	-5.1	Decreasing	5.4367
May 2010 - Nov 2010	7.82	Increasing	8.4517
Nov 2010 - May 2011	-3.06	Decreasing	3.3862
May 2011 - Oct 2011	5.44	Increasing	6.0914
Oct 2011 - Nov 2015	-7.82	Decreasing	8.6547
Nov 2015 - May 2016	-7.48	Decreasing	7.6626
May 2016 - Oct 2016	6.8	Increasing	6.9414
Oct 2016 - May 2017	-11.22	Decreasing	11.1957
May 2017 - Oct 2017	0.68	Increasing	0.6413

Regarding the trend of volume change, it has been found that the addition of water (in monsoon season) through the rainfall is following a declining trend whereas the removal of water through the evaporation in following an inclining trend. The rate of removal of water from the lake is observed faster than the rate of filling the lake with water. The study suggests that the condition was not that much threatening before 2011, whereas it is a matter of great concern for us, as the rate of precipitation has rapidly decreased "Figure 8" and the rate of evaporation has rapidly increased "Figure 9" in the recent years.

5. Conclusion

The study can be concluded with the following points:

1) Study suggests that the rate of evaporation is rapidly increasing and the rate of addition of water is gradually decreasing, in the recent years (2015-2017).
2) It is a matter of concern for the Lonar lake ecosystem, as continuous lowering of water level and reduction of volume can create threatening situation for the depletion of Lonar Lake.
3) It is to be believe the global warming and climate change is the major cause for such unexpectedly events.
4) Remote Sensing techniques can be use more frequently for regular monitoring such unique lakes in order to preserve their biodiversity.
5) The study has purely based on the remote sensing inputs and techniques, which can further be enhanced and accuracy can be increased by performing the ground truth verification.

Therefore, the study demonstrates the emerging potential of space technologies (Satellite Remote Sensing) over the traditional methods. It is cheaper and time consuming. However, one has to be restrict himself up to a certain accuracy level, because present remote sensing sensors have minor errors and can't produce as accurate as lab based results. But it the widely accepted tool for covering a large area in one synoptic view. Hence, combination of both the methods (lab based & remotely based) can give the best results for any study.

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