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Monitoring volume fluctuations of Indian reservoirs from space

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ABSTRACT

Lakes and reservoirs, a prime source of water supply for many settlements, are to be monitored at regular intervals of time for efficient usage. But many of these are remote and inaccessible for regular supervision. Remote sensing has been a breakthrough in the field of surveying, making it possible to directly monitor the volume of these water resources from space. In this paper, we estimate the volume of selected reservoirs in India using radar altimetry data and optical satellite imagery (such as Landsat). Two prominent reservoirs Ujjani and Govind Ballabh Pant Sagar were selected for the volume estimation and monitoring. The estimated volume was compared with the ancillary data (published reports) and the results are promising for "Indian Reservoir Monitoring from Space". We further developed a Quantum GIS plugin to support a fast and efficient reservoir volume monitoring with changing water-levels. The limitation of the methodology outlined is that the reservoir volume can be estimated only up to the deepest radar altimetry data available for the reservoirs of interest. The paper also outlines the commercial and scientific potential of this technology, particularly in Indian reference. Using satellite images with higher spatial resolution, the surface areas of the reservoirs could be more accurately measured and hence the volume computed.

Keywords: Remote sensing, Optical satellite imagery, Radar altimetry, Reservoir volume estimation, Earth Gravitational Model (EGM)

1. Introduction

Water, the stimulator of the socio-economic and cultural development of humanity on Earth, is the most basic natural elixir of life. Monitoring the capacity of inland water bodies is utile and critical for supervising water resources, climatic changes, flood control etc. But the high investment, maintenance, deployment difficulties, running costs and slow data dissemination characteristics of in-situ or traditional ways made such data collection mechanisms unpopular in many economies especially for remote, inaccessible areas. The radar altimetry emerges as an efficient alternative to monitor periodic variations in large water bodies (Oceans) at global scale and has potential to measure inland water surfaces as well (R.J.J. Dost et al.). This eliminates the need for surveying on the ground and provides the reservoir capacity entirely based on Earth-orbiting satellite data.

The methodology involves merging of two freely available satellite datasets: Landsat optical imagery and radar altimetry over two Indian reservoirs namely Ujjani and Govind Ballabh Pant Sagar, for remotely computing the temporal change in their water levels and hence their capacity. At present, the radar altimetry data is available for only 'four reservoirs' in India. We chose to take up two among the four to demonstrate the methodology. The prerequisite to carry out such a volume computation is to use a temporal sequence of Landsat imagery and radar altimetry, both covering the same time interval. The instantaneous shoreline of the water body obtained from Landsat image is characterized by a different water level. The corresponding height is estimated from the radar altimetry data close in time to the optical image. A temporal sequence of such paired optical and radar altimetry data thus provides a bathymetric profile which can in turn be transformed into frustum volume sections. Finally a comparative study was made with the ancillary data.

2. Technique

Radar Altimetry data could be utilized for sensing water levels from space (Lee-Lueng Fu and Anny Cazenave, 2001). It can render a space-based water level gauge such that with lower satellite revisiting time, we get an average over a footprint from altimeter-derived measurements. The considered footprint is smaller than the extent of the reservoirs under study.

Table 1: Reservoir minimum surface area versus altimetry footprint size

Lake / Reservoir	Minimum Surface Area (km^{2})	Altimetry Footprint size (m)
Ujjani	189.946	350
Gobind Ballabh Pant Sagar	289.735	350

Satellite radar altimetry measures the time taken by a radar pulse to travel from the satellite antenna to a surface and back to the satellite receiver, which can be translated into distance measurements, i.e., the range between satellite and the water surface. The satellite orbit has to be accurately tracked and its position is determined relative to an arbitrary reference surface, an ellipsoid (S. Vignudelli et al., 2011). The individual satellite height values are given with respect to a defined reference ellipsoid datum. Altimetry lake/reservoir level data from Topex/Poseidon, Envisat (ESA) and ERS-2 missions are validated using gauge-level time-series. Combined with precise satellite location data, altimetry measurements yield reservoir/lake-surface heights.

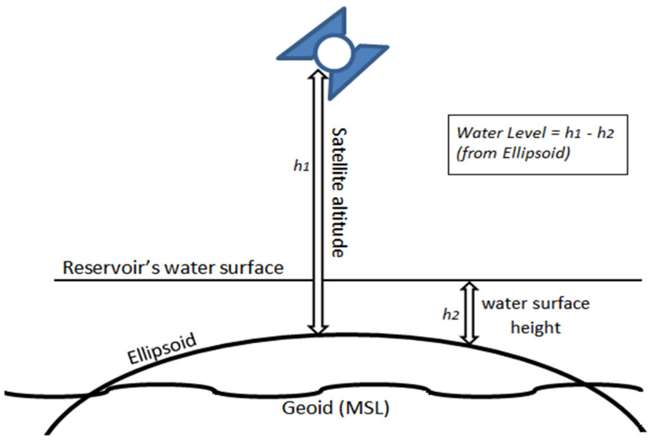
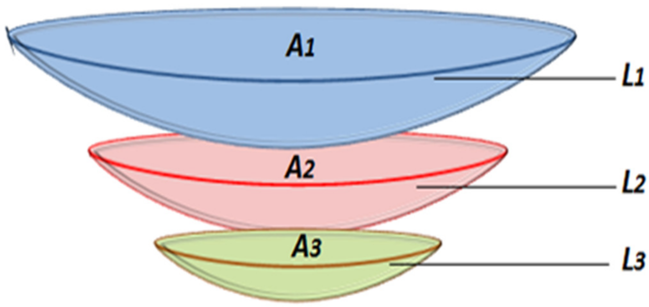


Figure 1: Reservoir water-level computation from Satellite Altimetry

The technique, integrates radar altimetry with multi-temporal optical remote sensing products to infer change in water volume on the basis of relation obtained between the two parameters, Lake water level and lake surface area (R. Abileah et al., 2011).

Let's consider the two temporal observations, the water surface areas A_n for n =1, 2...N, from LANDSAT imagery and water levels L_n for n=1, 2…N, from satellite radar altimeters. Most preferably, the two time series should have time synchronization, but this is rarely the case. These nadir-looking satellites have a temporal resolution of around half a month, but not matches on exactly same days. Normally, Landsat provides image acquisition rate ≤ 1 per month. Hence the radar altimetry data (L_n) is chosen to match the temporal availability of Landsat image (A_n). Each Landsat image provides the outline of the shoreline at a corresponding water level. The surface area of a reservoir/lake can be determined from a satellite image by mapping its extent. As the lake is characterized by its large surface area a small variation in water level represents a considerable change of storage volume.

This gives us a procedure of constructing a reservoir water volume-indicator using the surface area of the lake from the optical imagery and the corresponding water level from radar altimetry. The volume of a pyramidal frustum is derived by Heron's formula, as follows:



$$\Delta V_{12} = \frac{|L_1 - L_2|}{3}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right)$$

$$\Delta V_{23} = \frac{|L_2 - L_3|}{3}\left(A_2 + A_3 + \sqrt{A_2 A_3}\right)$$

Figure 2: Volume Calculation Using Heron's Formula

Where (L_1, L_2, L_3) is the span of observed water levels with corresponding surface areas A_1, A_2 and A_3.The sum of these series of consecutive frustums is calculated as the equation precisely applies for small intervals in water levels. Arranging the temporal area measurements sorted in ascending order with their corresponding levels gives pair-wise volume computation. Summing all the incremental volumes provides the total capacity. When the span covers dry bed to maximum capacity of the reservoir, the total volume can be computed reliably. If the full range of water levels cannot be observed (i.e., the reservoir is always partially filled) the approach outlined here is useful for the upper most layer (the water level below which altimetry data was unavailable) and leaves the bottom portion unknown. Thus the water capacity derived by this method applies to this top layer.

Once the bathymetry of the reservoir (a by-product of the outlined method) is obtained, the water level at any time may be derived by using just the areal extents mapped from any optical imagery, which is widely available, as compared to radar altimetry data.

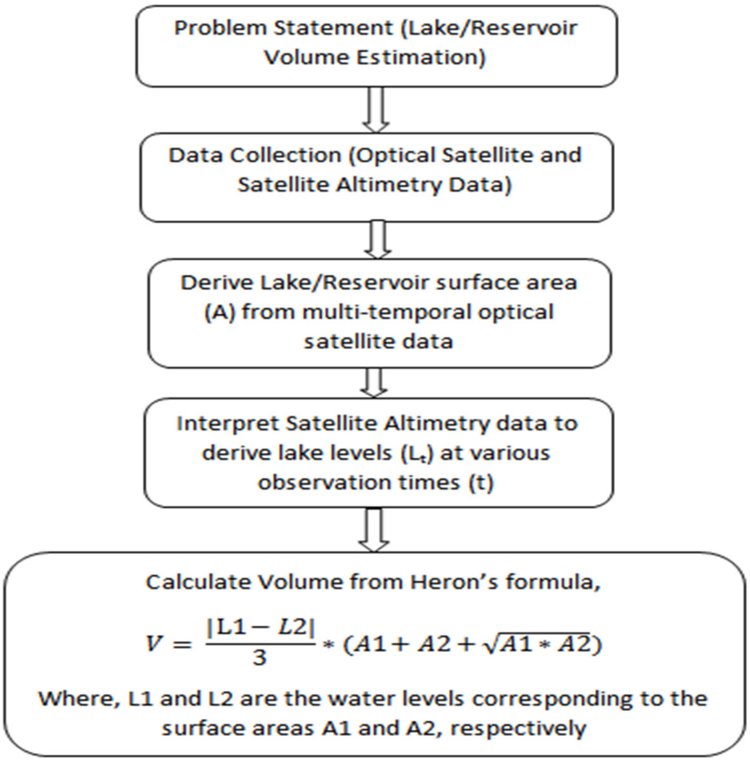


Figure 3: Methodology Flowchart

3. Volume Estimation & Monitoring

The methodology is applied to the following Reservoirs in India:

1. Ujjani (Maharashtra)
2. Govind Ballabh Pant Sagar (Uttar Pradesh)

The bathymetry of these reservoirs is obtained from radar altimetry and optical data. The volume is computed using Heron's Formula. During the period 1999-2011, these reservoirs have both long-term satellite coverage and simultaneous ground truth obtained from traditional water-level gauges. As previously mentioned, the prerequisite to carry out such a volume computation is to use a temporal sequence of Landsat imagery and radar altimetry, both covering the same time interval. The verification of the method is then established by showing repeatable results. The results estimated from altimetry are compared with the available ancillary data.

3.1 Study areas

Ujjani Reservoir (18°04′26″ N, 75°07′12″ E) is built on the River Bhima, a tributary of the Krishna River, located near Ujjani village of Madha Taluka in Solapur district of the State of Maharashtra in India. It is the terminal water body in the Upper River Bhima, which originates from Bhimashankar in the Western Ghats. The Dam constructed in June 1980, is the third largest reservoir in the state with a catchment area of 14,858 square kilometers.

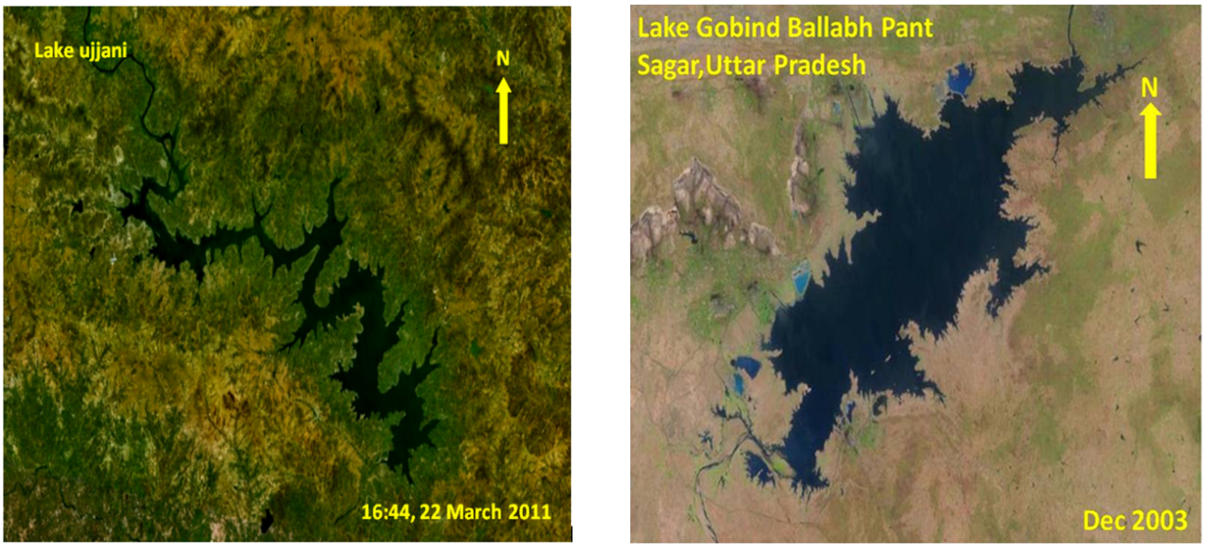


Figure 4: Lansat-7 Images (TCC) of Ujjani and Govind Ballabh Pant Reservoir

Govind Ballabh Pant Sagar (24°09′44″ N, 82°48′40″ E) is a man-made lake situated in southern region of Sonbhadra district in eastern Uttar Pradesh and partly in Sidhi district of Madhya Pradesh. It was constructed in 1962 on River Rehar near Renukoot having a catchment area of 12,865 square kilometers. The water stored in the reservoir is released into River Son periodically for irrigation purpose throughout the year.

3.2 Data sources

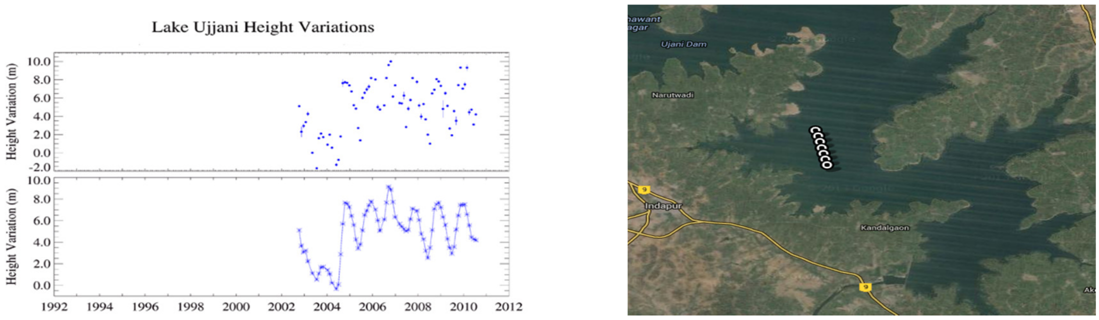
The following online databases are used for the study area:

1. EarthExplorer(USGS):- http://earthexplorer.usgs.gov.in

This works as a centralized repository for obtaining all optical imagery (Landsat) and DEM data. Being user friendly, it also facilitates to save custom searches.

2. PECAD (USDA):- http://www.pecad.fas.usda.gov

This provides radar altimetry data based on Topex/Poseidon, Envisat, ERS missions, etc. It gives a region-wise updated and assorted data with required corrections. The data is presented in graph (height variations versus year) and summarized text format with a provision of its interpolation to EGM2008. A sample radar altimetry dataset:



(a) (b)

Figure 5: Ujjani Reservoir height variations from Envisat altimetry data (a) and its satellite tracks (b)

Shown in figure 5(a) and 5(b) are the relative lake height variations computed from Envisat altimetry data for a given satellite overpass, and is based on the height profile across the reservoir on one particular observation day. One satellite overpass is chosen to be the reference overpass, and the profile of height variations across the lake, for that date or cycle, become the reference profile for that reservoir.

Essentially the reference profile becomes a unique reference datum for that particular lake; it is the profile to which all other overpass profiles are compared to. We converted the time series values to an approximate mean sea level datum (EGM2008) by calculating:
i) the average elevation of the lake's reference datum profile and

ii) the average elevation of the lake's geoid profile (which may be positive or negative), and then subtracting ii) from i).

3.3 Mapping the reservoir extent

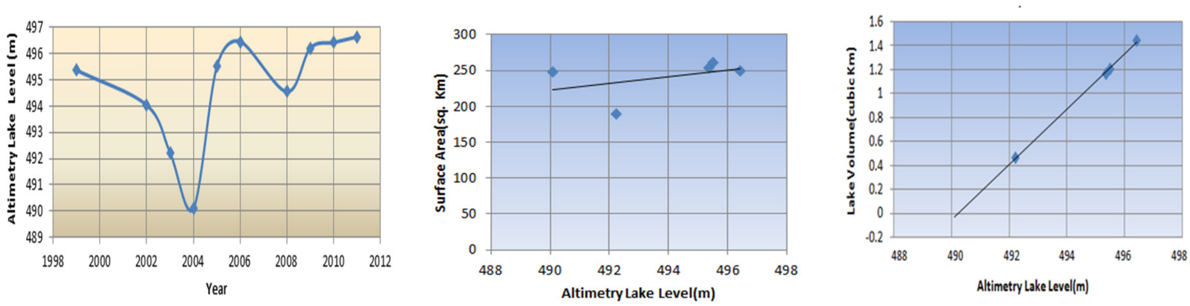
To map the varying reservoir area, freely available optical imagery (Landsat) is gathered from Landsat-7 ETM+ sensor, having a spatial resolution of 30 m. Pan-sharpening technique is further applied to enhance the spatial accuracy of multispectral images. Since we are interested only in the extents of reservoir, other image processing techniques are not employed. This shows the simplicity of the methodology. Landsat True Color Composite (TCC) was used for mapping purposes. Conventionally, manual mapping methods are employed for obtaining the reservoir boundary, but considering the complexity of the reservoir boundary an approach using ASTER DEM of the reservoir area is utilized to reduce the mapping time. The ASTER DEM gives a snapshot of the water surface when the image was acquired. Since the water surface at any point of time represents contour level of the reservoir, the water extent from the Landsat image can be matched to the nearest contour from the ASTER DEM. Manual reshape of the water extent was carried out at some places to improve accuracy. We mentioned about the limitations of the methodology that the volume can only be computed up to the last altimetry data available. We need not perform rigorous calculations to get the lake/reservoir bed nor do we require that information from other resources. We only need levels from altimetry for volume computation and monitoring. The results of mapping are as follows

(a) (b)

Figure 6: Mapped Extent of Ujjani (a) and Govind Ballabh Pant Sagar reservoir (b) from optical imagery (Landsat)

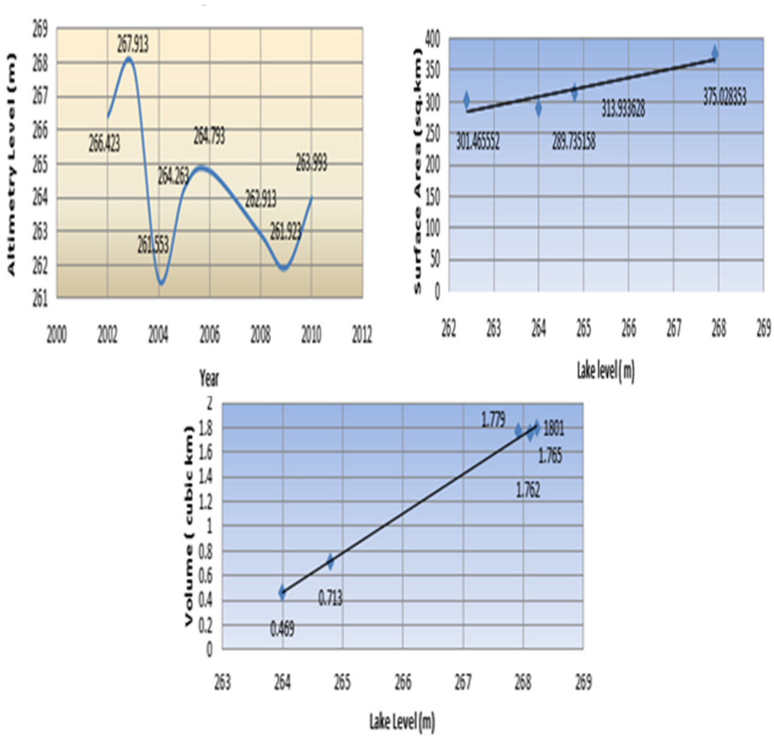
3.4 Volume Computation (Heron's Formula Implementation)

The water level of Ujjani reservoir varied over a range of 6.3 m during the period 1999-2011 as represented in Figure 7(a). The water capacity derived by this method thus applies to this top 6.3m layer. Volume extrapolation beyond this depth is not attempted. Figure 7(b) shows the computational steps leading to estimating the water volume which includes the scatter plot of observation data, with the radar altimetry on the x-axis and corresponding Landsat derived water surface areas on the y-axis. The optimal fitting polynomial equation is plotted on the graph that describes a functional relationship f(x). Most of the data is close to the fitted function and the scatter that remains in the observation data, is possible due to inaccurate area computation using Landsat (30m) but could be improved using higher spatial resolution images. The data suggests that the RMS radar altimetry errors are 5-10 cm. Not bad, even for an in-situ gauge. Figure 7(c) is the water volume as determined from the Heron's volume formula. The volume is relative to the lowest level over the observation period, not the full reservoir volume.



(a) (b) (c)

Figure 7: Temporal changes in surface area (from optical imagery) vs. altimetry levels and water capacity of Ujjani Reservoir from Heron's formula



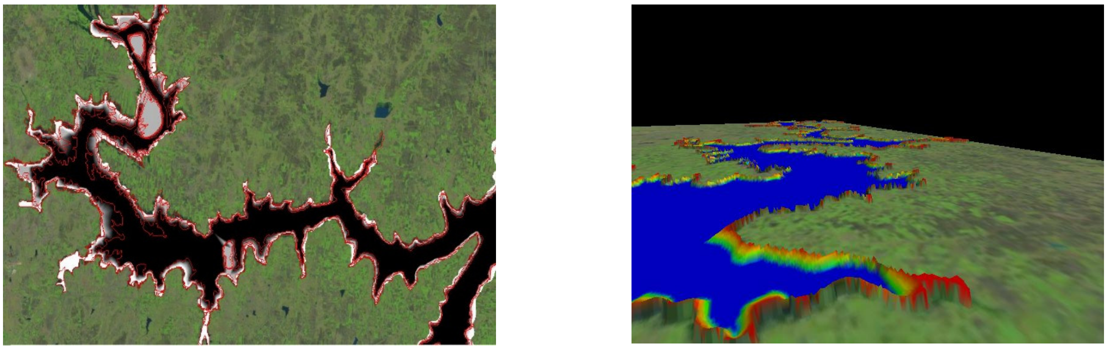
(a) (b) (c)

Figure 8: Temporal changes in surface area (from optical imagery) vs. altimetry levels and water capacity of Govind Ballabh Pant Sagar from Heron's formula

The same computational steps are applied for Govind Ballabh Pant Sagar. During the period of 2002-2010 the water level of reservoir Govind Ballabh Pant Sagar varied over a range of 6 m. The water capacity derived by this method thus applies to this top 6 m layer of the reservoir. Figure 8(b) shows the scatter plot of observation data with the radar altimetry on the x-axis and corresponding Landsat derived water surface areas on the y-axis. Figure 8(c) is the water volume as determined from the Heron's volume.

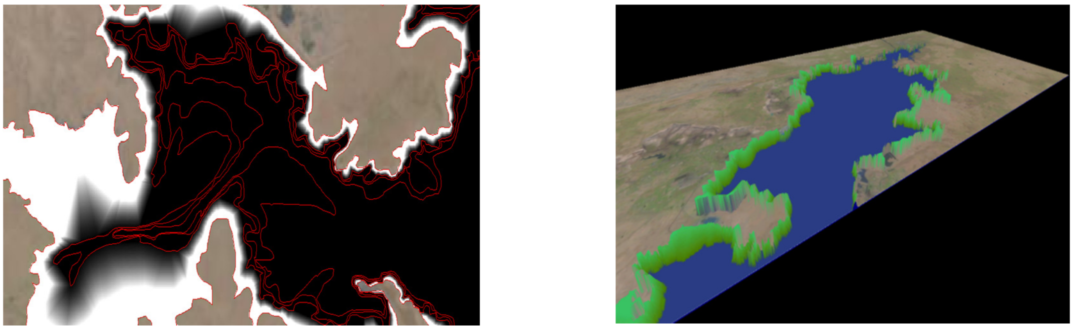
3.5 Bathymetry

A series of area water level data then define a series of contour lines, hence providing inputs to bathymetry. Thus the mapped extents of reservoir area acted as contour levels and were used in making an approximate DEM for the reservoir. The different contour levels of this remotely-sensed bathymetry of all the reservoirs were taken from the radar altimetry data.



(a) (b)

Figure 9: Ujjani reservoir bathymetry (b) using contours (a)

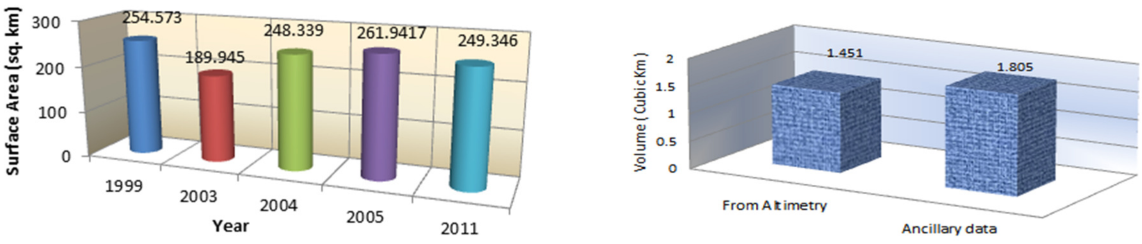


(a) (b)

Figure 10: Govind Ballabh Pant Sagar bathymetry (b) using contours (a)

4. Results and discussion

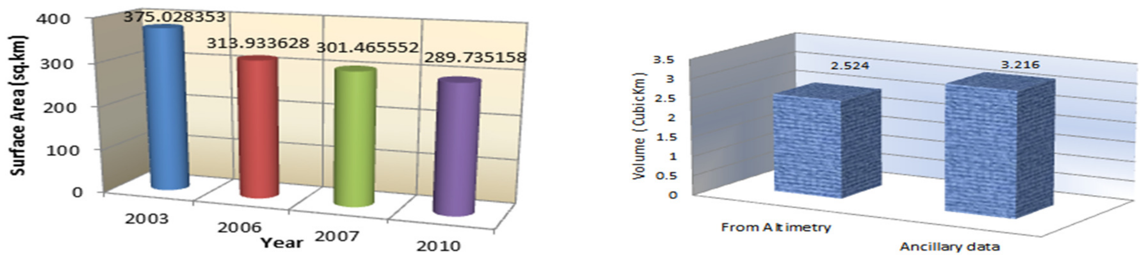
In 2003, water from Ujjani reservoir was released to compensate the water starved villages in Karnataka. Consequently the trend captured by this method show a drastic decrease in surface area for this year. Govind Ballabh Pant Sagar comes under a most arid area and a frequent drought prone area, as claimed by the Indian Meteorological Department, Pune. Uttar Pradesh has a humid subtropical climate most part of the year. The variations in the surface area during the year 2004 are uncomprehending, as there was a lack of quantifiable rainfall for so long which continued to adversely affect the surface area and most human activities in nearby surroundings creating a drought situation (http://rahat.up.nic.in/disaster_management.htm). Figure 13 shows the multi-temporal map prepared from Landsat optical imagery of Ujjani and Govind Ballabh Pant Sagar.



(a) (b)

Figure 11: Bar chart of year wise changes in surface area (a) and comparative study of volume obtained from different methods (b)

The methodology yields a comprehensive overview of hovering change in water storage over a time series. As such, the remotely-sensed lake storage changes appear to be sensitive indicators of nearby river discharge variations.



(a) (b)

Figure 12: Bar chart of year wise changes in surface area (a) and comparative study of volume obtained from different methods (b)

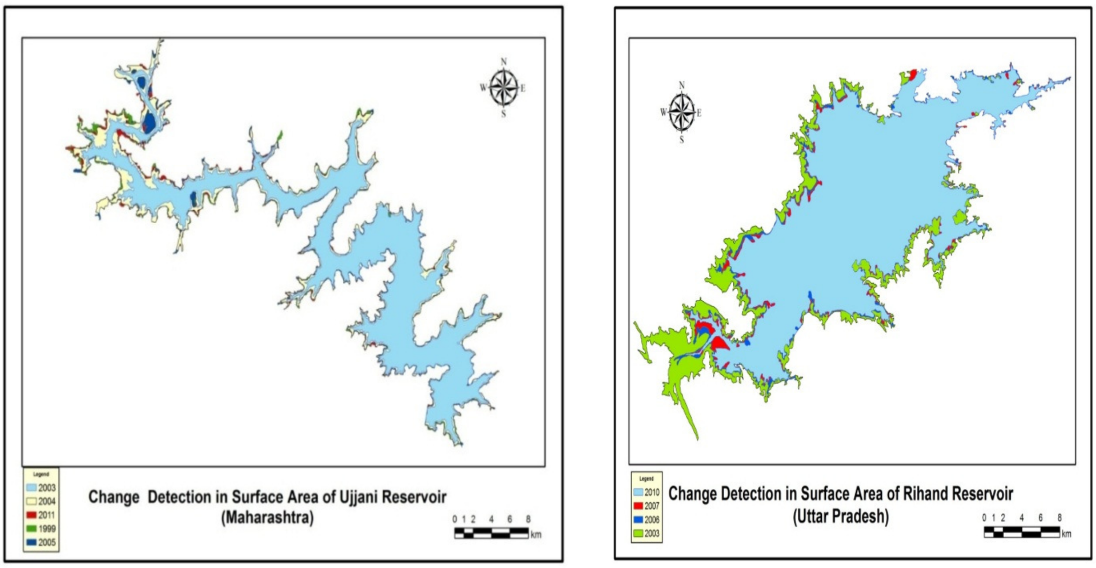


Figure 13: Surface Area Change detection maps of reservoirs Ujjani and Govind Ballabh Pant Sagar

Finally a comparative study of the volume of the reservoirs is made using the available ancillary data (CWC Bulletin, 2009 & 2013). The volume is relative to the deepest level over the observation period, not the reservoirs full volume. The difference between the observed water volume derived from Heron's formula and ancillary data indicates proximity in measurement. It is ascertained that the results obtained has a "volume under-estimation" for reservoirs, Ujjani and Govind Ballabh Pant Sagar. This under-estimation of volume is as expected. The difference could possibly be due to the volume that is not computed below the deepest altimetry data available for the reservoirs.

Table 2: Comparison of volume of the reservoirs computed from different methods

Reservoir Name	Volume from Ancillary data for known water levels (cu.km)	Volume from Altimetry data using Heron's formula (cu.km)	Volume Error between Ancillary data & Heron's formula (cu.km)
Ujjani	1.805	1.451	0.354
Govind Ballabh Pant Sagar	3.216	2.542	0.674

5. Software development

5.1 Reservoir volume estimator

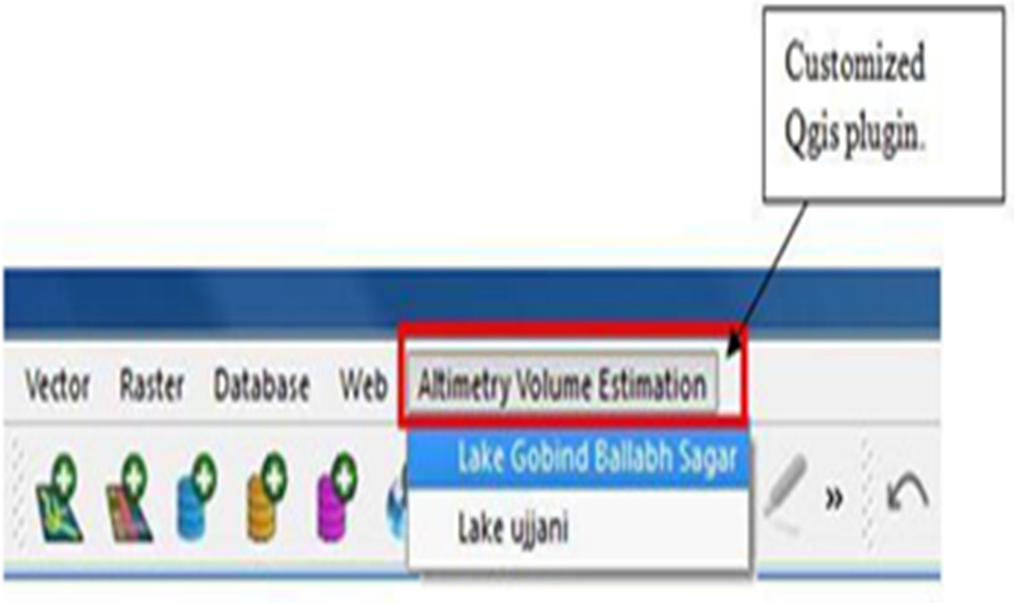
To provide a fast and efficient way towards volume estimation of reservoirs with varying water levels, an automated computational system is required. We project a software plugin that can keep track of the temporal reservoir height variations derived from radar altimetry satellite data sources and perform reservoir volume estimations (Heron's formula) using the mapped files for the short-listed reservoirs in India.

This plugin is designed for Quantum GIS, an open source GIS package. The GUI gives ease to monitor reservoir water volume in a quick and efficient manner. The user just needs a reservoir vector file with its surface area enclosed (a polygon). The tool is developed using Python3.3 and PyQt4 for designing the front end.

5.2 User instructions

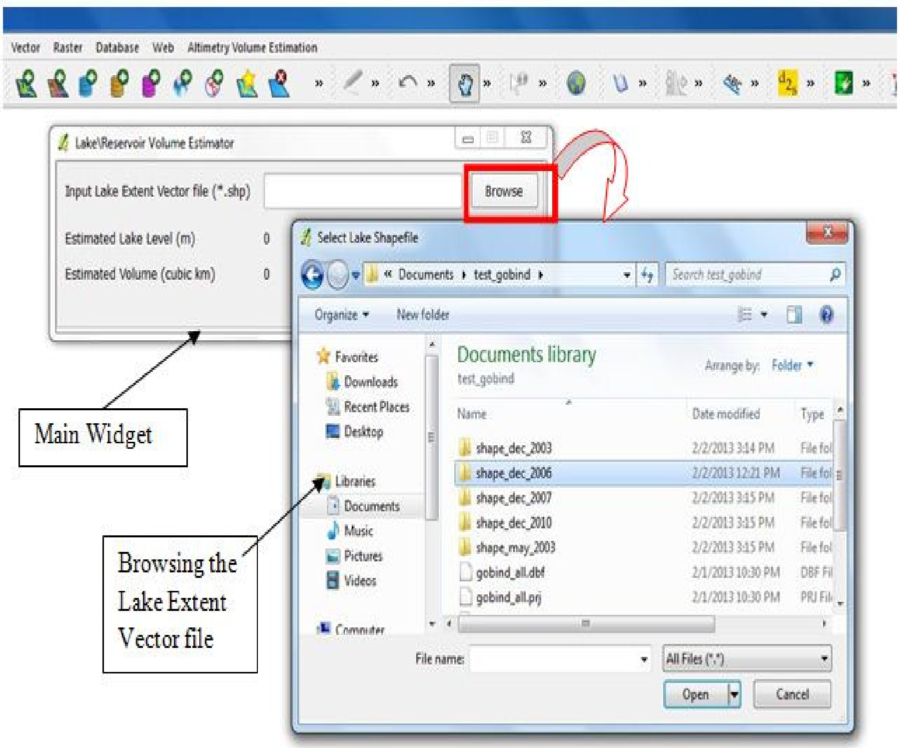
The user can use this plugin to compute reservoir water levels and perform volume estimation for the supported reservoirs namely Ujjani Reservoir (Maharashtra), and Govind Ballabh Pant Sagar Reservoir (Uttar Pradesh). The software is developed in a generic fashion that it can be used for any number of reservoirs to provide an automated volume computational way. All that is required is to provide a suitable vector file representing the lake area for corresponding water levels, as described in methodology. The enhanced versions of the estimator can offer the advanced capabilities of a mapping the extent, generating plots, and statistics of the temporal change in volume and lake levels. Following are the snapshots of the system in use

Step 1



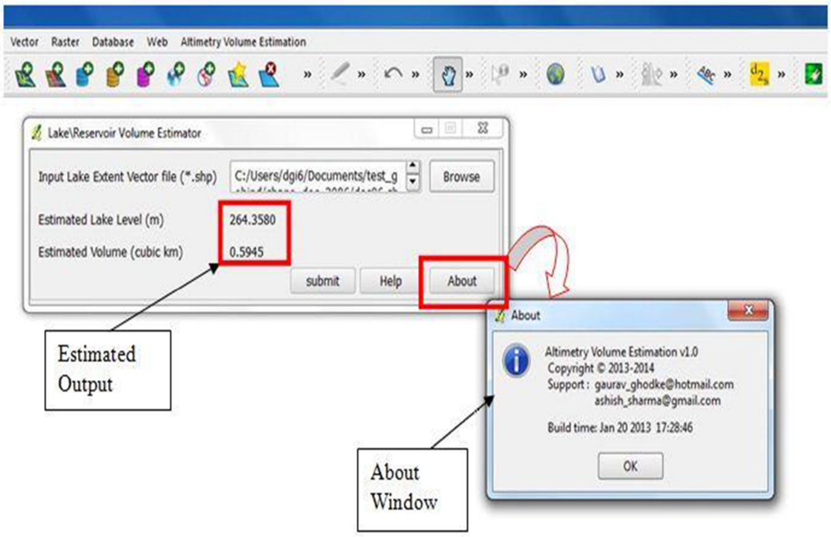
Get the plugin installed in Quantum GIS. Click on the "Altimetry Volume Estimation" button on the menu bar and select the interested reservoir to be monitored.

Step 2



Browse and select the intended reservoir's shape file (.shp) for which the user the wishes to estimate capacity. Shape file should contain specific attributes [refer section 5.3].

Step 3



After clicking the submit button, the lake level and volume will appear on the estimator's panel as shown in the above figure.

5.3 Usage tips

The required input vector file should be a Shapefile i.e. any (*.shp) along with Shapefile shape index (*.shx) and Shapefile attribute (*.dbf).

The feature class containing polygon feature must have two fields "Id" and "Area". The "Id" field helps the tool to discriminate between the different reservoirs.

The capacity of the reservoir estimated is in "cubic kilometer" and reservoir levels in "meter" having a precision of 4 decimal points.

5.6 Conclusion

Lately, remote sensing techniques are mature enough to calculate a lake's water surface variation, which usually is quite difficult to derive from ground measurements. National space agencies such as NASA, ESA and INPE have setup free public web data-bases that provide imagery of satellites instruments like Landsat or CBERS optical and IR sensors, Terra/MODIS, SRTM or Envisat/ASAR. As addressed by UNFCC, there will be a need to a continuous and automatic survey of lakes/reservoirs worldwide in the next few decades (J.F. Cre´taux, 2011).

The objective of this study was to demonstrate the use of freely available Landsat and satellite altimetry datasets to establish a calibrated, satellite data-driven, space-based water level gauge for reservoirs and validating it with reliable in-situ data. This practical, affordable and promising approach is demonstrated for multi-temporal reservoir water-volume analysis on reservoirs Ujjani and Govind Ballabh Pant Sagar for the period 1999 to 2011.This methodology and the software-tool is so developed provide a fast and efficient manner of monitoring reservoirs levels and volume over traditional in-situ methods. The early results shown here suggest that even similar-appearing lakes can display individual behavior with respect to their three-dimensional inundation geometries. The results show that the satellite-driven lake level modeling approach could satisfactorily capture the patterns and seasonal variations of the lake water level fluctuations.

From this study, we suggest that globally available satellite altimetry data provide a unique opportunity to study similar ungauged basins in different parts of the world. Radar altimetry has great potential to provide solutions which were not deemed feasible hitherto. Notwithstanding the increasing use of this technology world over, it has not yet been available in India. However, this technology has the potential of saving the precious national resources and providing better understanding of several problems which are difficult to comprehend otherwise, due to the limitations imposed by conventional data collection techniques. Needless to state, speedy collection of accurate hydrographic data, greatly reduces the cost escalations resulting from the delays in project work. It is worth noting that surveying and mapping operations take most valuable time in a project's life, thus influencing the ultimate cost substantially. Furthermore, Radar altimetry may prove to be the most suitable technology to measure Indian reservoirs, which in absence of appropriate hydrographic data become difficult to manage. India is prone to natural disasters of varied form resulting in heavy losses of life and wealth. Radar altimetry data have potential to be effective in many disaster management programs, including the most frequently occurring floods. High-resolution and accurate hydrography generated by Radar altimetry is most suitable to further the scientific understanding of natural phenomena, e.g. the floods and the coastal environment.

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