Tide-induced geometrical changes in Chilika lagoon using remote sensing

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This article presents hourly data from four tide gauge locations in the Chilika lagoon vis-à-vis satellite data, to study the tidal influences on the geometrical changes in the lagoon. The satellite-derived highest area and perimeter are 864.76 km^2 and 1512 km respectively, consistent with the field-observed occurrences of the low and high tides. The geometrical changes of 5.4% (44.36 km^2) in area, and 24.8% (300.83 km) in the perimeter, in one month duration, solely because of the tides are considerable changes. High radiometric resolution of the sensor provided improved delineation of land–water boundary of the lagoon shores.

Keywords: Chilika, lagoon, RESOURCESAT-1 AWiFS, remote sensing, tide gauge.

TIDES can have a significant impact on the biological and geometrical characteristics of a lagoon[1,2]. Chilika lagoon, situated on the east coast of India, in the state of Odisha, is the second largest brackish water lagoon in the world[3]. Ramsar Convention designated it as a Wetland of International Importance, since 1 October 1981. The pear-shaped lagoon sprawls about 64 km in length NE–SW and about 5–18 km in width from south to north, covering an area of ~ 1165 to ~ 906 km^2 during the monsoon and summer. The catchment area of the lagoon is around 4200 km^2. The tides in this region are semi-diurnal. Chilika lagoon is a shallow water body with the deepest point of about 3 m in the southern end and shallowest as low as 0.60 m in the northern end. It opens in the Bay of Bengal (BoB) through an artificially opened mouth approximately 200 m wide. The Government opened a new artificial mouth in 2007 by cutting and dredging the sand spit to increase the eutrophication and wildlife habitat, which were declining because of decreasing salinity after the closure of the northern natural opening into BoB[4,5].

Chilika lagoon epitomizes one of the biodiversity-enriched ecosystems of the world. It confronts significant tidal upheavals semi-diurnally. The preservation of this tropical ecosystem from natural hazards and other threats becomes an obvious field of study, including aspects such as variability of the nutrients in the lagoon, salinity, water flux measurements, tidal variations, etc. The lagoon is oriented parallel to the coast between the Eastern Ghats and BoB and connects to BoB through a long, narrow outer channel separated from sea by a narrow spit. The high rate of predominant northeasterly long-shore transport (littoral drift) along the east coast of India shifts the mouth of the lagoon northeastwards.

Though the lagoon is consistently monitored through *in situ* data-collection campaigns from inside, remote sensing methods have proven to be an extremely efficient and accurate means of monitoring the lagoon[6]. The geomorphological and water quality changes occurring in the lagoon have been monitored by infrared index (IRI) and normalized difference vegetation index (NDVI) using RESOURCESAT-1 and IRS (Indian Remote Sensing Satellite)-1D data[5]. Panda and Mohanty[7] classified the vegetation in Chilika lagoon based on NDVI using IRS-1D and RESOURCESAT-1, and water quality and flow modelling. As the size of the lagoon is substantially large, one can exploit the remote sensing-based techniques for monitoring of its eutrophication, water quality, geomorphological changes, and aquatic and surface vegetation. Satellite sensors detect water-leaving radiance, which contains contributions to radiance from various constituents present in the water (e.g. suspended sediments, underwater vegetation, chlorophyll *a*, etc.) from an area (called spatial resolution) in various electromagnetic channels (called spectral resolution).

This article addresses two main objectives: (1) To substantiate the RESOURCESAT-1 AWiFS (Advanced Wide-Field-of-view Sensor) capability to delineate land–water boundary of coastal water bodies, e.g. Chilika lagoon. (2) To report the changes in the geometrical characteristics such as the area and perimeter of Chilika lagoon as it fluctuates with a full month tide cycle using an improved radiometric (10-bit) and spatial resolution (56 m) of RESOURCESAT-1 AWiFS data.

Materials and methods

Study area

The study area lies between 19°28′–19°54′N and 85°05′–85°38′E in the coastal regions of Odisha. Figure 1 shows a true colour image of Chilika lagoon (Landsat 7 ETM + L1T). The Eastern Ghats hills surround the eastern

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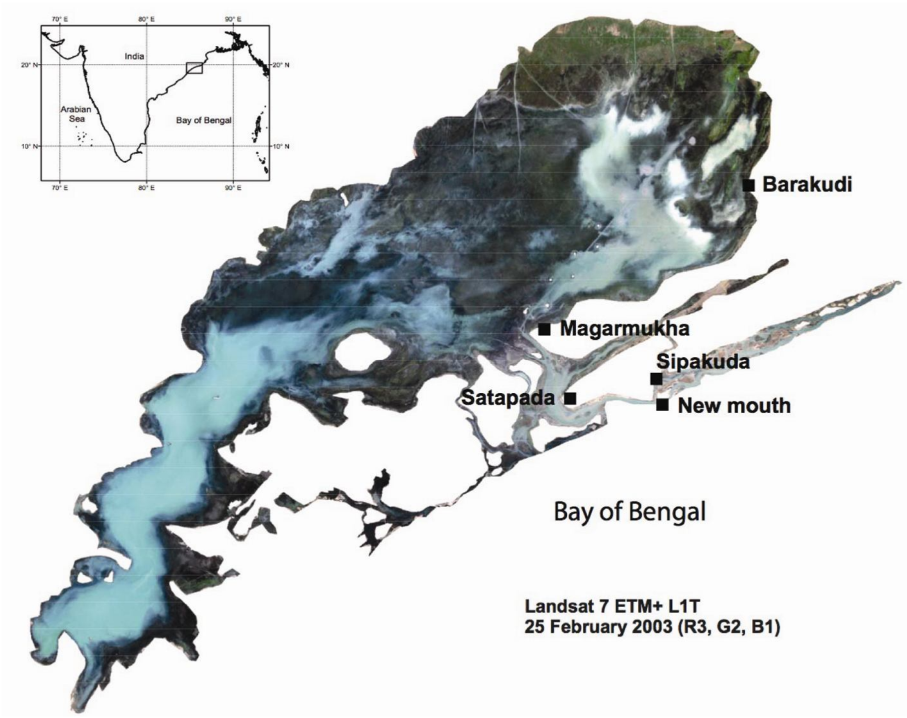

Figure 1. Map of Chilika lagoon. The true colour image (R3 : G2 : B1) of the lagoon acquired by Landsat 7 ETM + L1T on 25 February 2003, shows the locations of tide measurements and new mouth opening.

and western margins of the lagoon. There are 52 small rivulets that drain freshwater into the lagoon in the north, the main rivers being the Daya and Bhargavi, distributaries of the Mahanadi[5]. The BoB seawater enters the lagoon through a mouth midway along the east coast length of the lagoon.

AWiFS methodology

The present article uses, for the analysis, an aggregate of seven imageries that are cloud- and haze-free, acquired from RESOURCESAT-1 AWiFS on 1, 5, 6, 10, 15, 20 and 25 March 2004. The Indian satellite, IRS-P6 (officially named RESOURCESAT-1), launched on 17 October 2003, carried AWiFS amongst other sensors (Table 1). The rocket PSLV-C5 (Polar Satellite Launch Vehicle) launched the satellite into a Sun-synchronous orbit at an altitude of 817 km and the equatorial crossing time is 1030 h IST (Indian Standard Time). The Indian Space Research Organisation (ISRO) performed a complete post-launch data quality evaluation (DQE; radiometric and geometric) during the calibration mode of acquisition (commissioning). Inflight light emitting diode (LED)-based calibration was programmed during night pass in realtime. On-board calibration data were compared with the ground reference data to perform radiometric calibration. The AWiFS has an improved radiometric resolution (10-bit quantization) over previous sensors (6-bit). Manjunath and Muralikrishnan[8] have provided the radiometric calibration details of RESOURCESAT-1 AWiFS.

Table 1. Major specifications of RESOURCESAT-1 AWiFS

System parameter	Value
Spectral bands	Band 2: 0.53–0.59 μm (green)
	Band 3: 0.62–0.68 μm (red)
	Band 4: 0.77–0.86 μm (NIR)
	Band 5: 1.55–1.70 μm (SWIR)
Spatial resolution	56 m at nadir
Swath	740 km (two cameras A and B combined)
	370 km (each)
Saturation radiance	Band 2: 53.0
(mW/cm^2/sr/μm)	Band 3: 47.0
	Band 4: 31.5
	Band 5: 7.5
Integration time	9.96 ms
SNR at saturation radiance	> 512
Quantization	10-bit

NIR, Near infrared; SWIR, Shortwave infrared; SNR, Signal-to-noise ratio.

Digitization (delineation of the land–water boundary) was carried out using ERDAS IMAGINE 8.5 software. The National Remote Sensing Centre (NRSC), Hyderabad, provided the satellite imageries. RESOURCESAT-1 AWiFS data were imported to ERDAS using generic binary data type and unsigned 16-bit format. The sub-image of the Chilika lagoon was extracted from the full scene. Atmospheric correction of the images was not considered as it is assumed that the changes in the top of the atmosphere remained uniform over the whole study area. The geo-correction of the image was done using another geo-corrected image. The projection used is geographic (latitude/longitude) and WGS-84 (World Geodetic Survey) as datum, with units in decimal degrees converted to polyconic, units in metres.

Accuracy of boundary determination

It is important to select a band that best discriminates the land–water boundary to compute the area protruded by water. The water absorbs most of radiation in the near infrared band 4 (0.77–0.86 μm) of the AWiFS. This band demonstrates its utilization as a marker of land–water boundary. Middle infrared band 5 (1.55–1.70 μm) also shows strong absorption by water, including muddy water. All seven imageries were imported into the software one at a time and land–water boundary from band 4 was digitized. Then, the area and perimeter of the lagoon in each of the satellite imageries were computed. Once the geo-corrected imageries are vector-digitized, the products of area and perimeter can be extracted using the software. At locations where it was difficult to clearly differentiate the land–water boundary using band 4 (0.77–0.86 μm), assistance from band 5 (1.55–1.70 μm) and other band combinations was taken to ascertain the best demarcation line. None of the bands could independently clearly demarcate the land–water boundary because of ambiguities in water-leaving radiance detected by the satellite sensor in the areas of mud, turbid waters, bottom reflection, underwater/surface weed infestation and optically complex waters. The minimum resolvable area and perimeter are 0.31 km^2 and 0.06 km respectively, given the 56 m spatial resolution of the AWiFS. The computed perimeter of the lagoon does not include the isolated islands; the presented perimeter is only the external periphery of the lagoon that separates water from the mainland.

The dates of satellite images were selected to match, as much as possible, with the occurrence of high or low tides at four tide gauge stations – Magarmukha, Barakudi, Sipakuda and Satapada (Figure 1). The selected locations were at relative proximity to the new mouth where seawater enters the lagoon, the turbidity is very high, and the tidal effects are predominant. The range of tidal variations in the interior of the lagoon (western shore) is comparatively small. The tide data were logged on an hourly basis, and the water level at each station was corrected for the mean sea level (MSL).

Results

Figure 2 shows the MSL-corrected water levels at four locations. Table 2 provides the corresponding computed area and perimeter of the lagoon. It is obvious from most plots that the tides in Chilika lagoon are semi-diurnal. The vertical line in each plot indicates the equatorial crossing time of RESOURCESAT-1 at 1030 h (IST). The negative values on the *y*-axis in Figure 2 indicate the water level below MSL. The water level at the four stations is dependent on the shoreline and bathymetry; therefore, the absolute values of tidal heights are redundant. The data were available only from 6 to 18 h for all dates at Barakudi. Complete 24-h tidal data were available for seven dates (1, 5, 6, 10, 15, 20 and 25) during March 2004 at other locations. As the seawater enters the lagoon, one meets the highest water levels at a station in the following sequence: Satapada, Sipakuda, Magarmukha and Barakudi (Figure 2). Gradual decrease in the tidal heights as one goes farther from the mouth is clearly seen in Figure 2. The lowest tidal height (–0.59 m) occurs at Barakudi, which is the farthest station from the mouth. Barakudi does not show any patterns of semi-diurnal nature of tides in the lagoon. Satapada experiences very high tidal currents, as it is the main channel of entry/exit of seawater into the lagoon, with highest tidal variations, i.e. 0.83 m (Table 3).

Sipakuda, though being closest to the mouth, experiences lesser tidal variation than that at Satapada because of hindrance of islands that reduce intensity of tidal currents. Barakudi shows a very little change in tidal height (0.26 m) over a month's period. This implies that interiors and aloof shores of the lagoon, at a distance from the mouth, experience little tidal influence. Sipakuda shows the highest variation in tidal height (1.15 m) over a month, whereas average tidal height over a month is highest (0.52 m) at Satapada (Table 3).

Water levels at stations are interpreted at the time of satellite pass, i.e. high, mid and low water levels are read along the vertical line in each plot in Figure 2. The observations at Magarmukha are: 5, 6 and 20 March (high tide); 10 March (mid), and 1, 15 and 25 March (low). The observations at Barakudi are: 25 March (high); 1, 15 and 20 March (mid), and 5, 6 and 10 March (low). The observations at Sipakuda are: 10 and 25 March (high); 5, 6 and 20 March (mid), and 1 and 15 March (low). The observations at Satapada are: 5, 6, 10, 20 and 25 March (high), and 1 and 15 March (low). All four stations show high tide on 25 March, and low tides on 1 and 15 March. The tide predominantly hits Satapada and Sipakuda, being closest to the new mouth to the sea compared to Barakudi, which shows marginal tidal variations. From Magarmukh to Barakudi because of shallow depth (about 0.60–1 m), the presence of submerged and floating vegetation also seems to affect the observed water levels.

The computed highest area and perimeter match with the observed occurrence of high tide on 6 and 25 March (Table 2). The computed lowest area and perimeter match with the observed low tide conditions on 20 March. The field-observed intermediate tide conditions and water levels at four stations correlate with the satellite-derived area and perimeter, thus validating the remote sensing approach. The relationship between area and perimeter is

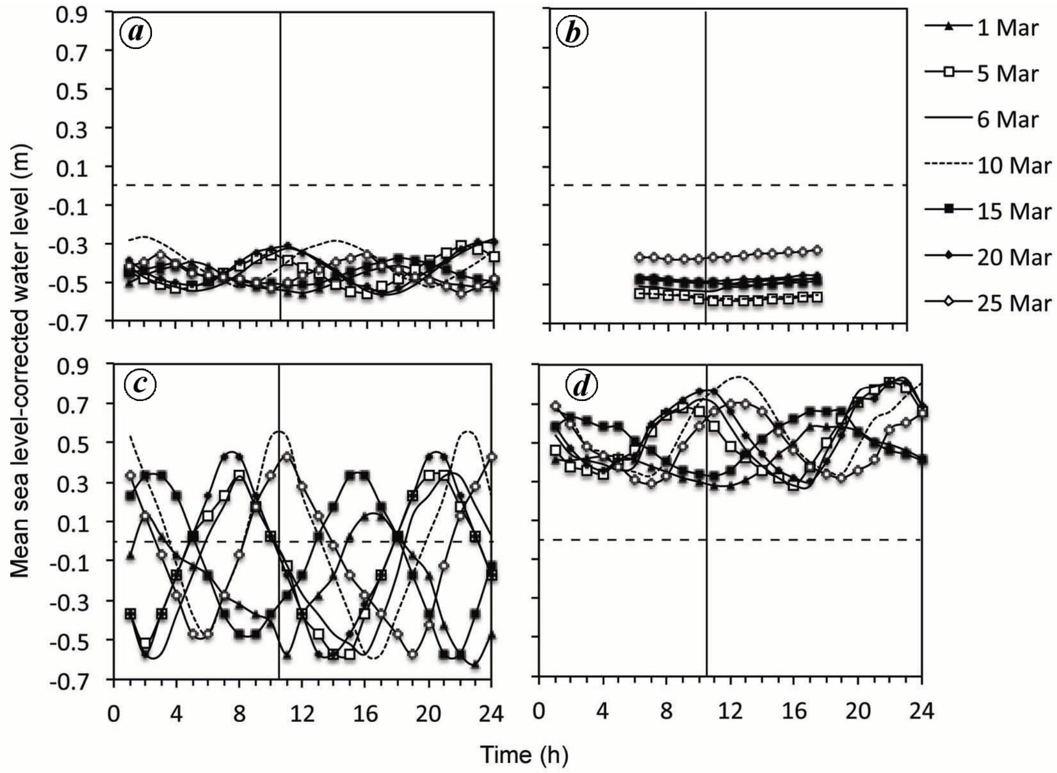

Figure 2. Mean sea level-corrected water levels at four locations: ***a***, Magarmukha; ***b***, Barakudi; ***c***, Sipakuda; ***d***, Satapada. The vertical line shows the equatorial crossing time of RESOURCESAT-1 at 1030 h (IST). The horizontal broken line represents the mean sea level.

Table 2. Lagoon area and perimeter derived using band 4 (0.77–0.86 μm) of RESOURCESAT-1 AWiFS on different dates

March 2004	Area (km^2)	Perimeter (km)
1	853.83	1448.71
5	860.00	1366.83
6	864.76	1369.40
10	820.40	1455.79
15	844.42	1379.17
20	838.00	1211.18
25	864.00	1512.00
Standard deviation	16.21	96.34

dependent on numerous factors, e.g. shape of the shoreline, local bathymetry, presence of surface vegetation, etc. Therefore, the AWiFS-derived area and perimeter do not exhibit a one-to-one relationship with each other. Another reason for a moderate correlation (not shown) between water levels and the computed area and perimeter is the instant AWiFS pass, while the tide (high or low) persists over a longer time-period. There is considerable time gap between the change of water level at a station and the time of tide entering the lagoon through the new mouth. For example, it takes about an hour for the tide from the new mouth to reach the western shore of the lagoon. Thus, the computed area and perimeter at 1030 h (IST) correspond to tide conditions different from that at the new mouth. The water residence time of Chilika lagoon, depending on the time of tidal circulation, varies seasonally from ~7 days during monsoon to 120 days during premonsoon[9,10]. The range of fluctuation in the computed area is from 820.40 km^2 (10 March) to 864.76 km^2 (6 March). An analogous range of fluctuation in the computed perimeter is 1211.18 km (20 March) to 1512 km (25 March). Thus, the satellite-derived changes in area and the perimeter are 44.36 km^2 (5.4% change) and 300.83 km (24.8% change) respectively. This change in area and perimeter is likely to increase during monsoon (June–July). Statistical analysis of image-derived area and perimeter showed a standard deviation of 16.21 km^2 and 96.34 km respectively (Table 2).

Shallow water and small lagoons, because of shallow bathymetry and gently sloping shores, go through discernible and significant shoreline/geometrical changes caused by tidal fluctuations. The results found in this study may be applicable to any shallow water lagoon or coastal water body having an area of about 800 km^2 or larger lagoons that face dramatic impacts by the tides.

Discussion and conclusion

This article reports the role of tides on the geometrical characteristics such as area and perimeter of Chilika lagoon as it fluctuates to a full month tide cycle, using an

Table 3. Highest and lowest tidal heights (mean sea level-corrected) at four tide stations during March 2004. Sipakuda shows the largest variation in tidal height in a month, whereas average tidal height in a month is highest at Satapada. Negative values indicate the water level below mean sea level

Station	Minimum (m)	Maximum (m)	Variation (Maximum – minimum; m)	Average (m)
Satapada	0.28	0.83	0.55	0.52
Sipakuda	–0.62	0.53	1.15	–0.09
Magarmukha	–0.57	–0.27	0.30	–0.44
Barakudi	–0.59	–0.33	0.26	–0.49

improved radiometric (10-bit) and spatial resolution (56 m) of RESOURCESAT-1 AWiFS data.

Toward objective-1: a high, 10-bit radiometric resolution of AWiFS bands provided elucidated and improved delineation of land–water boundary of the lagoon. The minimum resolvable area and perimeter are 0.31 km^2 and 0.06 km respectively, given the 56 m spatial resolution of the AWiFS. As future suggestions, satellite imagery available every few hours (high temporal resolution) can be ideal for tidal observations in the lagoon. The results of this study can provide satellite-based inputs/outputs for carrying out various activities, tide-induced shoreline change detection, and management planning dependent on the timing of the tide arrival; for example, fishing, boat tourism, field data collection, etc.

Toward objective-2: the satellite-derived lowest and highest area and perimeter on 20 and 6/25 March, are consistent with the field-observed occurrence of the low and high tides on these dates. The total computed area affected by tides in the lagoon is 44.36 km^2. The intermediate tide conditions are significantly dependent on the local bathymetry, shore geometry, and presence of surface and submerged vegetation. The standard deviation in the calculation of area and the perimeter is 16.21 km^2 and 96.34 km respectively. Satapada and Barakudi experience highest (0.83 m) and lowest (–0.59 m) tidal heights during the whole month. Sipakuda experiences highest tidal height variation (1.15 m) over a month amongst the four tide stations.

The geometrical changes of 5.4% (44.36 km^2) in area and 24.8% (300.83 km) in the perimeter, in a time-span of one month, solely because of tidal variations (no monsoon), is quite considerable in a tropical wetland of international importance. These findings, using satellite-based remote sensing methods, have clearly demonstrated their utilization in monitoring the effects of monthly tidal fluxes on shallow water lagoons.

As suggestions for future work – with such a considerable influence of tides in Chilika lagoon, it would be interesting to see the corresponding changes in benthos and sedimentation attributed to the tidal inflows within the lagoon. The findings of this study can also assist in studies of the migration of surface and submerged floating weeds, and contaminants inside the lagoon in response to tidal fluxes.

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