

# A New Methodology for Virtual Water Level Gauges

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## Abstract

*Monitoring water stored in lakes and reservoirs is much needed in various countries for energy generation, food security and mitigating floods, among recurrent global issues. Natural and human-made open water bodies do not all have monitoring systems, this lack of regular information generates uncertainties in modeling, and increases unaccounted time-bound residuals in water balances. A large amount of water bodies storage variations are not monitored around the World. Here we show that this can be changed by the creation and the implementation of the concept of water Level Virtual Gauges (wLVGs) based on slope tracks upstream of water bodies, correlated to publicly available satellite remote sensing information returning water levels bi-monthly on average, sometimes weekly. An operational RMSE is found to be 12-52 cm height, depending on the characteristics of the upstream slopes used to calibrate wLVGs. This methodology is simple enough to be implemented for all medium to large reservoirs, but is also found successful for smaller rural reservoirs in tropical/sub-tropical countries. We anticipate that this can open globally distributed pathways to monitor open water bodies across the World, improve public databases on water storages and give management information for non/less-monitored water bodies.*

## 1. Introduction

Tracking water from space (Alsdorf and Lettenmaier, 2003 and Crétaux et al., 2015) is becoming strategic to manage Earth resources, especially within the threatening context of humanity exhausting the biosphere planetary boundary (Running, 2012). From the global freshwater, rivers and lakes are dependent on their declining heterogeneous gauging network (Shiklomanov et al., 2002) to inform about their discharge/volume status. Actual monitoring of lakes, reservoirs and other smaller/natural water retention areas is still an outstanding research issue. In many countries the implications can mean an economical constraint, to some others, life threatening natural disasters. Earlier development of radar altimetry (Birkett, 1998) has proven the potential of remote sensing of water stages within continental lakes and large rivers. Indeed, the water level of open water bodies is a vertical change, for which the most direct sensor is an altimeter (Getirana et al., 2010 and Flener et al., 2012). It also developed an important concept in the remote sensing of river discharge, the Virtual (gauging) Station or VS which is just a remote sensing proxy of a real gauging station where rating curves are known. Recognizing the capacity of optical remote sensing to delineate the water line, several research combined both remote sensing methods to estimate more accurately changes of water stages (Bjerklie et al., 2003).

Smith (1997) mentions that the exploitation of nadir-oriented radar full waveform is bearing large potential for river/water stage monitoring. He mentions the successful attempt of Koblinsky et al., (1993) to estimate river discharge stage at four sites along the Amazon using Geosat waveform data. Birkett et al., (2002) used radar altimetry to estimate river surface slopes and wave fronts dynamics on the Amazon river using Topex/Poseidon altimetry. Frappart et al., (2008) used Topex/Poseidon altimetry to estimate water level time series also in the Rio Negro river basin. Getirana et al., (2010) used altimetry from ENVISAT to generate from Virtual (gauging) Station (VS) water stages that were used as forcing/validation parameters for a hydrological model in the Negro River Basin. Birkett (2000) studied the Lake Chad surface levels variations by combining the altimetry from the Topex/Poseidon satellite and the area estimate from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer images in 1995-1998, using a simple pixel histogram technique with an accuracy of 10 cm rms. Birkinshaw et al., (2010) used ENVISAT and ERS-2 radar altimetry to supplement regular flow estimation methods in the Mekong, with Nash-Sutcliffe  $r^2$  moving from 0.884 to 0.935. Li (2010) derived the river width from GLAS product GLA14 elevation and Landsat ETM+. They derived an average water surface area between two reach

locations using Landsat ETM+ for a number of sites. For each site, they geographically computed a reach length, elevations and slope, which was the dividing parameter of the previous quantity. He et al., (2014) improved grayscale extraction methods from Synthetic Aperture Radar, using multi-stage segmentation to delineate with better accuracy the river channel side. Dubey et al., (2014) estimated stage records derived from the Envisat satellite of the European Space Agency and Topex/Poseidon of NASA/CNES for the period 2002–2010. The water levels permitted to estimate the monthly discharge and the annual water yield at six virtual gauging stations (VS) at the braided reaches of the Brahmaputra River. They needed to define a correlation from satellite-altimetry-derived stages and observed water levels, this was carried out for all VS for monsoon and non-monsoon seasons. Abreu and Maillard (2014) used Envisat and SARAL/Altika altimetry data (2007-2014) in Brazil. The data was corrected using a novel processing technique resulting in a relative precision of 0.24 m (RMSE). They used Landsat images to constrain volume changes from altimetry. Hossain (2014) used JASON-2 altimetry to make a satellite-altimetry-based flood warning detection system for Bangladesh and ran a 100 day operational skill test (June 1 - Sept. 9, 2013). Correlation for most of the flood warning stations ranged between 0.95 to 0.80 during the 1-8 days lead time range. The RMSE of forecast typically ranged between 0.75 m to 1.5 m at locations where the danger level relative to the river bed was more than an order higher (i.e., >20 m). Xu et al., (2004) used very high resolution remote sensing imagery from Quickbird-2 at ~0.6 m spatial resolution, visible near infrared sensors and an ideal return period of 1-3.5 days. They used one or two images per study area, and concentrated on the accuracy of geo-registration of the satellite images. Their ground data was extensive: stage, discharge, cross-sectional geometry of the Yangtze river and dual-frequency GPS survey of the river banks. After deriving stage to water discharge relationships for the period 1998-2001, they geo-registered the Quickbird-2 images to the dual-frequency GPS ground control points and assessed the water surface width from satellite. This input into the river channel geometry data permitted the extraction of the river stage. In turn, the river stage was included into the Stage-Discharge equations below to assess the water discharged. Timing between discharge data collection and satellite overpass were considered to be an outstanding issue. The accuracy range for the estimation of water discharge from space was found to be 92-98%. Sun et al., (2009)

used the satellite based width to assimilate the calibration of rating curves iteratively with a genetic algorithm and a hydrological model. The convergence of such rating curve parameterization permitted the inclusion of an observed width by remote sensing into their hydrological modeling process. In the near future, the Surface Water and Ocean Topography (SWOT) mission is planned to launch in the 2018-2020 period (Biancamaria et al., 2011). On board will be a Ka-band Radar Interferometer (KaRIN), which will have a wide swath. It will provide inland water surface elevation for rivers, wetlands and reservoirs with a spatial resolution from 2-60 m depending on ranges and along-track/off-track conditions, with a return period in the range of 20-30 days, generally comparable to the well-known Landsat satellites. The temporal and processing limits will not make SWOT an operational satellite, forbidding near real-time data streams of rivers/lakes/reservoirs water stage. However, the quality of the height data will provide full river cover, much like a Landsat image would do. Along reach, integrated water height derived from SWOT altimetry can open some research agendas in hydraulics that can permit modeling of water velocity, thus discharge. There is little doubt that absolute satellite-altimetry has a great future for water body altimetry, and that with the increasing reporting capability of additional satellites will be of great monitoring help in the future. Increasing coverage, return period and non-public domain availability are still of concerns. Thus, multi-source public domain satellites bearing higher spatial resolution should be investigated too, even though they may not directly report altimetry. This is experimented within this study, using the last of the most common (and long-standing) series of high spatial resolution publicly available satellites: Landsat 8. Here we show the creation and the implementation of the concept of **water Level Virtual Gauge (wLVG)** based on slope tracks upstream of water bodies, correlated to publicly available satellite remote sensing information returning water levels bi-monthly on average, and for some locations, weekly.

## 2. Methodology

The proposed methodology is measuring the presence of the waterline along a horizontal track, defined as the water Level Virtual Gauge (wLVG; Figure 1). The water line is estimated in this case from Landsat image. It is then correlated with the operational daily observations from various official sources (all recorded and checked). From this, a direct operational information can be found.

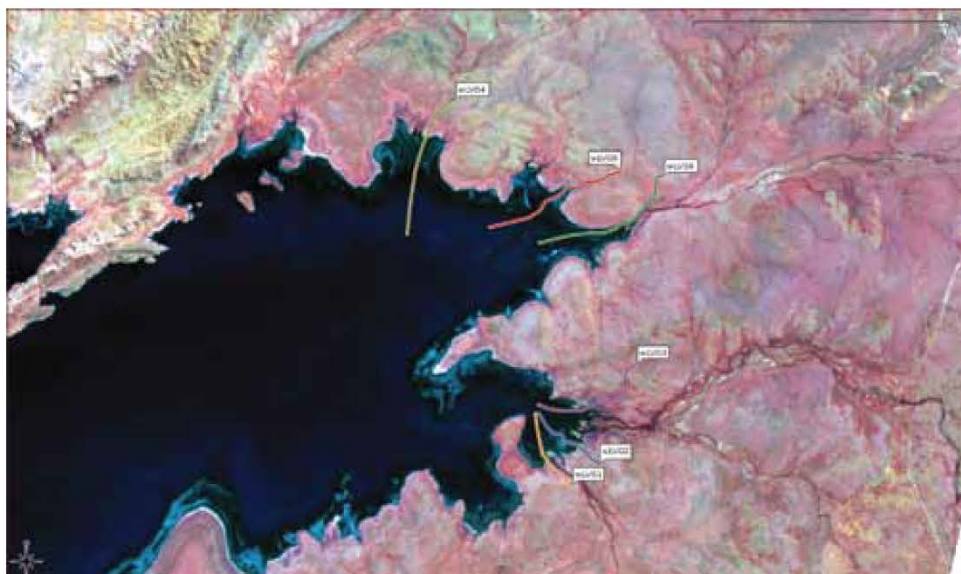


Figure 1: Lake Argyle, AU, (2013-04-23), tracks wLVG1-6

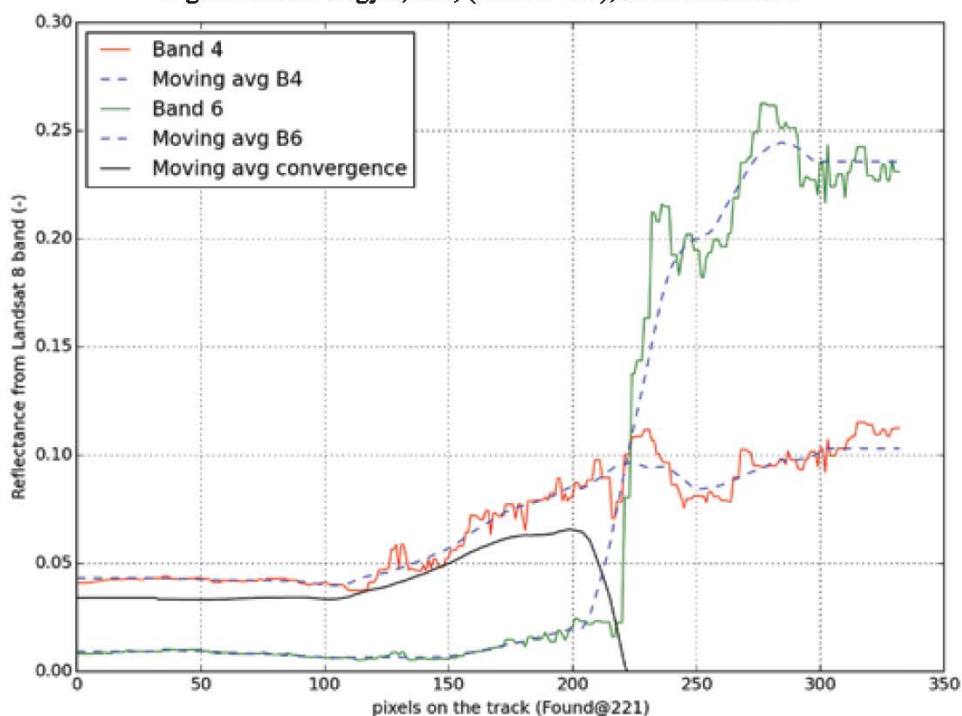


Figure 2: Convergence along the wLVG5 track (2013-04-23) from Figure 1

Though we used a given satellite sensor, its design is fairly common, and other similar sensors can be substituted. The public domain availability of Landsat was our main interest for accessibility reasons. Also, we used observed information of water levels, because of the high quality of the measurements, testing the upper limits of the type of correlations we could derive with wLVGs. Any other, less reliable source of data can be used eventually, when it comes to operationalization.

Landsat 8 has a target of 24 hours delivery, making it an interesting support for near real time monitoring (i.e. ~1-2 days) of the water reservoirs in a given watershed. However, Landsat 8 has a return period of 16 days, making it less interesting for emergency response on its own. Landsat 8 band 4 (Red) and band 6 (SWIR1) were used (Figure 2), downloaded with 15 m pixel size from Google Earth Engine (GEE, 2015) with a subset surrounding closely Nachchaduwa tank.

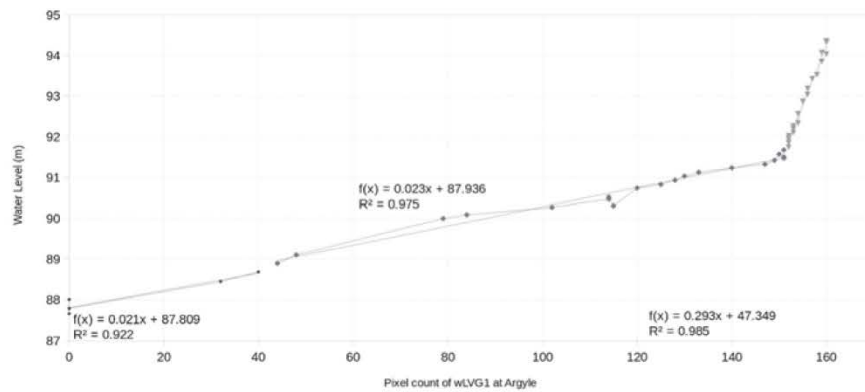


Figure 3: Lake Argyle wLVG1 calibration

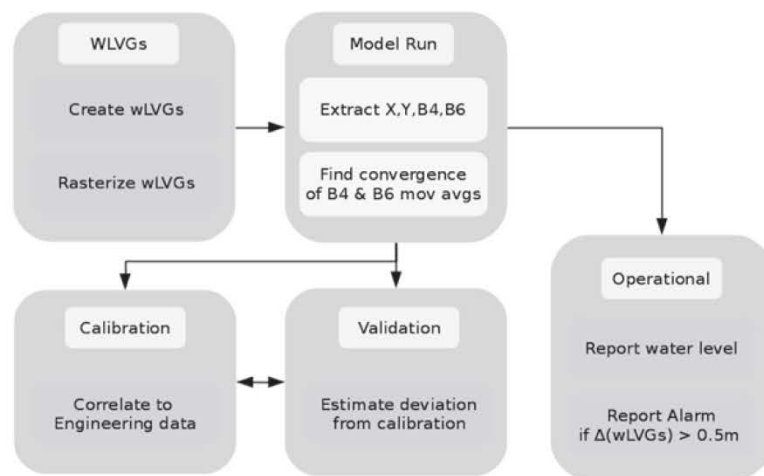


Figure 4: Methodology for wLVG

The data is available starting April 7<sup>th</sup>, 2013 onward, it is a LIT product, with Top of Atmosphere reflectance corrections. The red and the SWIR1 bands have a consistent difference in reflectance when bouncing off a water body. The SWIR1 band is absorbing more than the red band on water. Lake Argyle (128.742°E 16.1227°S ; Figure 2) is a much bigger water body (~700 Km<sup>2</sup>) than the further studied Pakistani tanks (~250 Km<sup>2</sup>) and the Sri Lankan tanks (~10 Km<sup>2</sup>), it is also under a very different climate, with less cloud frequency. Because of its sheer size and fortunate location, it has half of its area into two WRS-2 paths. The benefit of such location is that the Eastern Half of the Lake is visited every 8 days on average because of the small overlap in the swaths. We drew wLVGs (Figure 2) on this Eastern side of the lake to take benefit from such return period bonus configuration. We got the water level from the Bureau of Meteorology (see acknowledgements) and matched it with the wLVGs, Figure 3 shows wLVG1. It can be separated in two to three linear correlation parts. All three sections of lake Argyle have a good linear

fitting ( $0.92 < r^2 < 0.98$ ). Because of the high level of clouds in tropical countries like Sri Lanka, it is impossible to have full area cover, thus estimating a typical area-depth-volume relationship as proposed in Chemin and Rabbani (2011) is not a practical option. The Virtual (gauging) Station (VS) concept of (Birkett, 1998) was expanded and developed into the concept of water Level Virtual Gauge (wLVG) in this research (Figure 4). It is a vector line (curved), drawn by an operator, or by an algorithm, to go from a deep part of a tank up to a clearly defined shrub/vegetation area outside of plausible reach from the water level. This vector line follows a small slope as much as possible, to cover a higher vertical sensitivity for each pixel. Because of the cloud coverage, we developed two wLVG tracks for Nachchaduwa (80°28'57.37"E 8°14'59.93"N; Figure 5), a sri lankan tank of about 12 Km<sup>2</sup>, so that if one is covered by a cloud, the other may give a convergence result on the waterline (Figure 6). This proved interesting, as the patchiness of cloud does leave room to one of the track regularly.

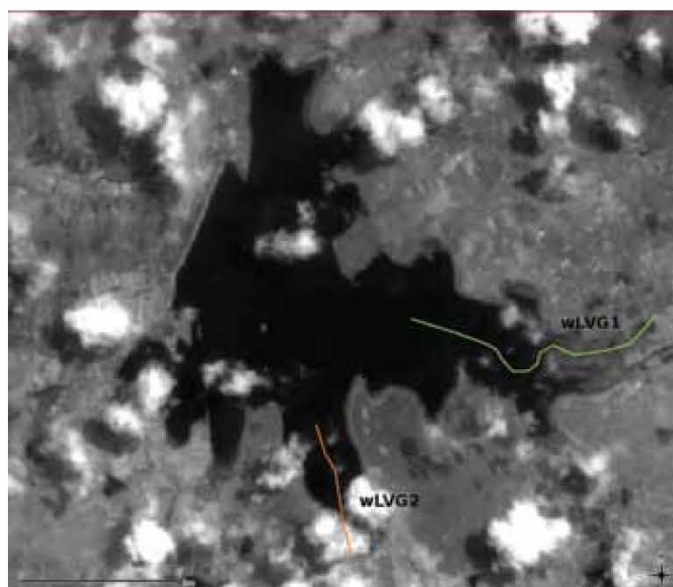


Figure 5: Nachchaduwa Tank (2013-05-25), with tracks wLVG1 & wLVG2

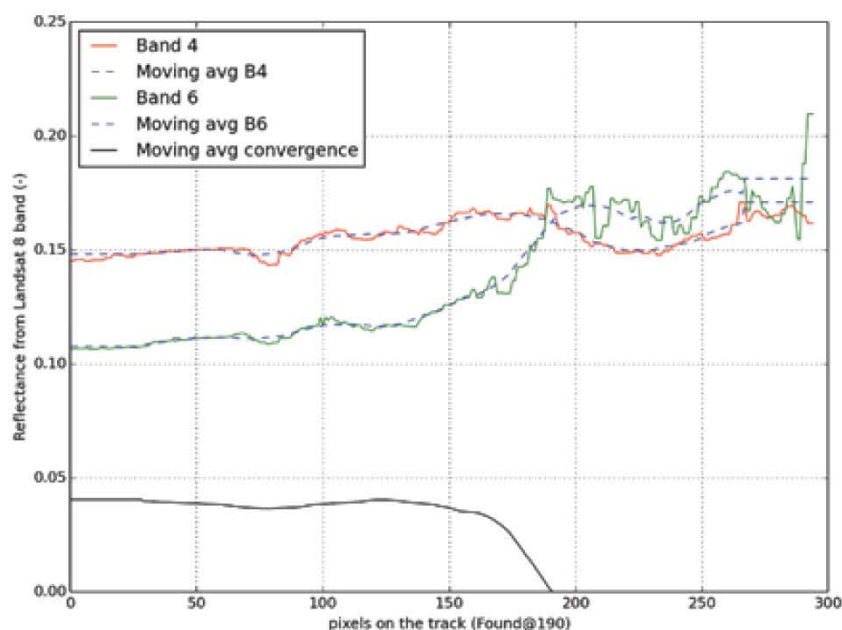


Figure 6: Nachchaduwa Tank convergence on wLVG1 track (2013-05-25)

The [calibration / validation / operational] procedures were entirely programmed using Free & Open Source Software. The main integrative routines were written in GNU/Linux Bash Shell scripts (GNU/Linux, 2015), with few Numerical Python scripts (NumPy, 2015), and using the Geospatial Data Abstraction Layer (GDAL, 2015). Calibration results in Figures 7 and 8 show that for the few initial temporal points, great fitting coefficients are found ( $>0.9$ ). As time accumulates, the fitting is not expected to stay linear as in the case of lake Argyle (Figure 3), though smaller tanks may have consistent slopes throughout (see below

linear fitting of Sri Lanka data). A similar experiment was done on the neighbouring Sri Lankan tanks of Nuwarawewa ( $80^{\circ}25'34.90''E$   $8^{\circ}20'26.85''N$ ) and Mahakandarawewa ( $80^{\circ}32'33.18''E$   $8^{\circ}23'6.13''N$ ), with more operational conditions. In each tank, five wLVG curves were drawn with less care than the first experiment, following simpler guidelines. Calibration water level data was only available for 2013. Calibration curves were screened for obvious outliers that found cloud interference when inspecting the images nullifying those data points.

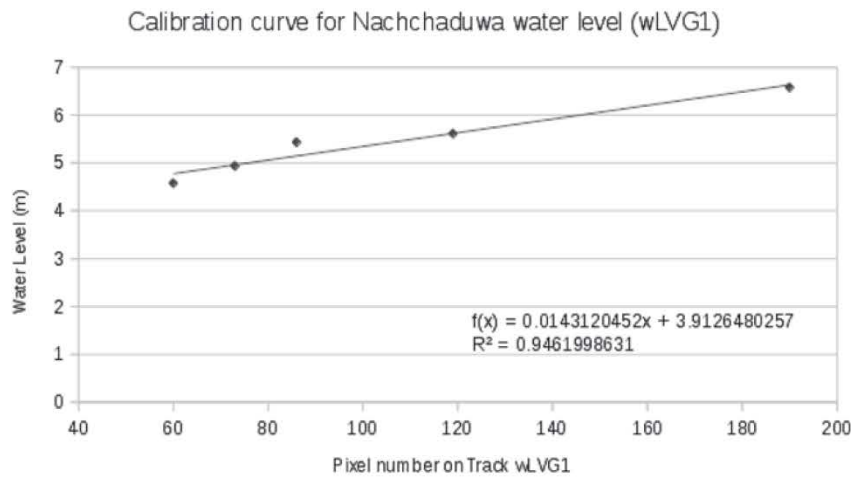


Figure 7: Calibration results for wLVG1

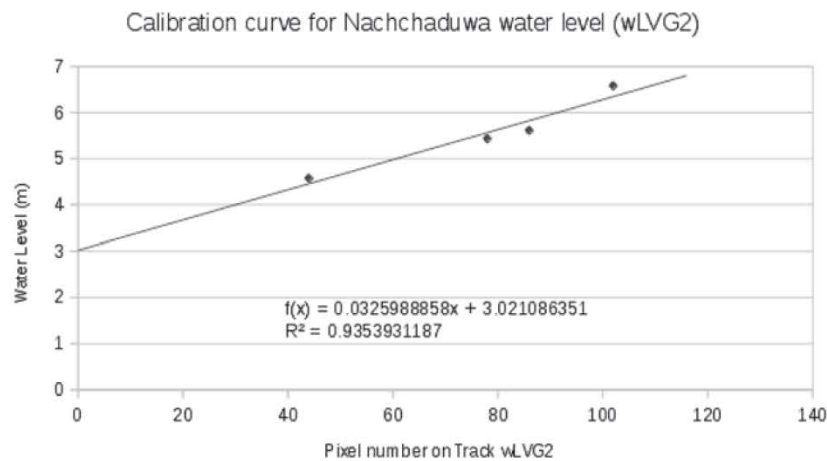


Figure 8: Calibration results for wLVG2

Table 1 summarizes the calibration results for Nuwarawewa, with variable strength of linear fitting, the tank was not emptying enough in 2013 to draw a full range of calibration levels, 2014 data was used, reducing the pool of validation samples. A way to increase accuracy is by lengthening artificially the slope length of the wLVG by drawing a line along the near horizontal of the slope contour lines, it increases the amount of pixels count for a smaller height increment. This is particularly easy to draw on long beaches of bare soil in finger like shapes upstream. In Table 2, Mahakandarawewa tank calibration shows linear relations holding well, and quite accurate, as the tank is large and upstream branches are making long flat fingers, which are most appropriate to increasing the design accuracy of wLVG tracks. Interestingly, wLVG5 could not converge enough times to reach any conclusion on a relationship. Validation of the Nachchaduwa Tank data was done on 2015 Landsat 8 imagery. The calibration equations were used to run the 2015

imagery data as it came online, informing the irrigation department about the estimated water levels, in order to cross-check their measurements. The first image received in the first week of 2015 was extracted from GEE (2015) and modeled according to the calibration data. The initial results are found in Table 3. Both wLVG tracks return values above 7 meters, the irrigation department informed that the tank was over-capacity during last weeks of December and started regulating early January 2015. The water level at design capacity of the tank is 25 feet (7.62 m), making the modeled values 0.21m and 0.49m below design capacity. Another image of Landsat 8 was found, which was missing from the GEE database, as it is a pre-WRS2 image. It is dated from March 2013, it was downloaded and the Top-Of-Atmosphere Reflectance (TOAR) was processed using GRASS GIS (Neteler and Mitasova, 2008) module *i.landsat.toar*.

Table 1: Nuwarawewa calibrating (2013-2014 data) &amp; validating mode (2014)

wLVG #	Cal offset	Cal gain	R <sup>2</sup>	Samples*	RMSE 2014
1	-3.7505913808	0.0480031223	0.92	13	0.15 (3 samples)
2	-3.9244714286	0.0686466165	0.85	10	0.38 (3 samples)
3	-1.4200820307	0.0353317905	0.71	10	0.12 (3 samples)
4	1.9495231474	0.0128129808	0.86	13	0.25 (3 samples)
5	-0.6804074589	0.0531748389	0.89	11	0.52 (4 samples)

\* More samples initially, but discarded due to cloud contamination

Table 2: Mahakandarawewa calibration (2013 data) &amp; validation (2014 data)

wLVG #	Cal offset	Cal gain	R <sup>2</sup>	Samples*	RMSE 2014 (m)
1	0.444658227	0.016575994	0.99	6	0.23 (1 sample)
2	0.578878717	0.016612440	0.99	8	0.28 (5 samples)
3	-0.92536453	0.0289487326	0.99	7	0.36 (3 samples)
4	-2.24949752	0.0556121727	0.97	7	0.18 (3 samples)
5	Failed	Failed	NA	2	NA

\* More samples initially, but discarded due to cloud contamination

Table 3: Nachchaduwa Tank Validating mode (2015-01-08)

wLVG #	Pixel index	Cal offset	Cal gain	Level (m)	Note
1	242	3.942648026	0.0143120452	7.41	Spilling
2	126	3.021086351	0.0325988858	7.13	Spilling

Table 4: Nachchaduwa Tank Validating mode (2013-03-21)

wLVG #	Pixel index	Cal offset	Cal gain	Level (m)
1	242	3.942648026	0.0143120452	7.40
2	103	3.021086351	0.0325988858	6.38 *

\* Alarm issued to operator

The sensitivity of the model had to be adjusted, since the moving average window is proportional to the track length (10% for B4 and B6 originally) and was overlooking smaller water bodies in the upstream for 2013-03-21 image. After the moving average percentage correction was done (10% for B4 and 5% for B6), the water level detection was appropriate for wLVG1, but did not permit to reach convergence for wLVG2 which should have happened at pixel index 134.

The model was developed with anthropogenic and topographic conditions upstream in mind, whereby large water found after an obstacle (first convergence) should be considered if the signal is strong enough. This image analysis shows the limit of the system where one track (wLVG1) does converge on the second peak, as expected (after sensitivity adjustments), but the second one (wLVG2) does not converge eventually. A warning is then raised when wLVG track estimations are too

different ( $\Delta L \geq 0.5$  m is the threshold for alarm), and operator is asked to give a choice after inspecting the satellite image (or with any other secondary information). Actual measured information was reported later by the Irrigation Department, permitting actual accuracy measurements to be computed (Table 5). Tarbela dam (72°41'49.76"E 34° 5'20.26"N) in Pakistan is a large dam (~250 Km<sup>2</sup>) on the himalayan Indus River. It is the largest earth filled dam in the World. We acquired monsoonal water level from Water and Power Development Authority (WAPDA) for 2013 and 2014. These values match 6 imagery data sets (Table 6). One of the image was cloud-ridden and had to be removed from the calibration set. The wLVG5 had another image removed as clouds covered the half-western part of the calibrating area, reinforcing the concept of multiple wLVGs for both calibration and validation under cloud variability.

Mangla dam (73°38'33.30"E 33° 8'26.29"N) in Pakistan is a large size dam (~250 Km<sup>2</sup>) on the himalayan Jhelum river. We set up the wLVGs downstream of Khadamabad and across Raipur vicinity. The sinuosity of the topography made it challenging to have several high quality wLVGs, though wLVG3 has a high R<sup>2</sup> value (Table 7), the points are not clearly aligned on the linear fitting, this could be fixed by a nonlinear fit, or by simply discarding this wLVG from the operational use. It turns out that the wLVG3 topography has a non-linear slope, maybe some geological features with different hardness created small topographical steps. This is clearly a limit in the method, unless one wants to use polynomial fitting, or as in the case of lake Argyle (Figure 3), several linear fitting sections. We recomputed the water levels for all dates for Mangla in the Figure 10 using data from the highest fitting, wLVG1.

Table 5: Nachchaduwa Tank Validation with observed water levels at/near spilling

Date	wLVG #	Level (m)	Level obs. (m)	$\Delta L$ (m)	$\Delta L$ (%)
2015-01-08	1	7.41	7.65*	0.21*	2.75*
2015-01-08	2	7.13	7.65*	0.49*	6.40*
2013-03-21	1	7.40	7.54	0.14	1.86
2013-03-21	2	6.38 **	7.54	1.16	15.38

\* Spilling \*\* Alarm issued to operator

Table 6: Tarbela dam calibrating mode (2013-2014 data)

wLVG #	Cal offset	Cal gain	R <sup>2</sup>	Samples*
1	1342.1937748979	0.4488374632	0.98	5
2	1314.3592123523	0.4019137963	0.95	5
3	1367.3978613519	0.2907152644	0.93	5
4	1354.963204126	0.3231189824	0.93	5
5	1369.41302383	0.4694010305	0.96	4

\* 6 samples initially, but discarded due to cloud contamination

Table 7: Mangla dam calibrating mode (2013-2014 data)

wLVG #	Cal offset	Cal gain	R <sup>2</sup>	Samples*
1	1106.962055381	0.2657913276	0.98	9
2	1069.840627256	0.335727800	0.96	9
3	1059.860915876	0.239149181	0.94	9

\* 10 samples initially, but one was discarded due to cloud contamination

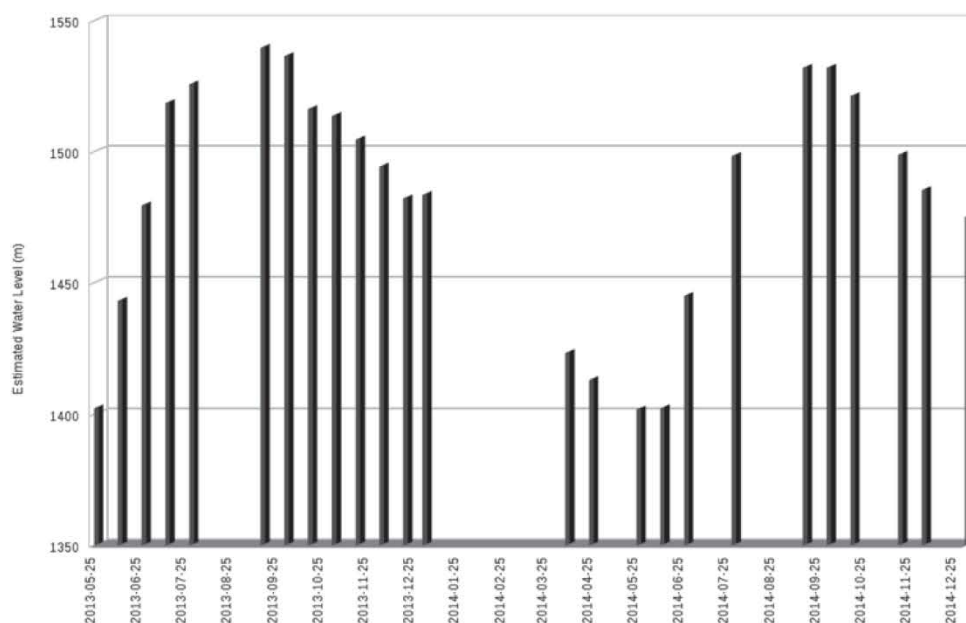


Figure 9: Tarbela dam reconstructed water levels (m) from Landsat 8

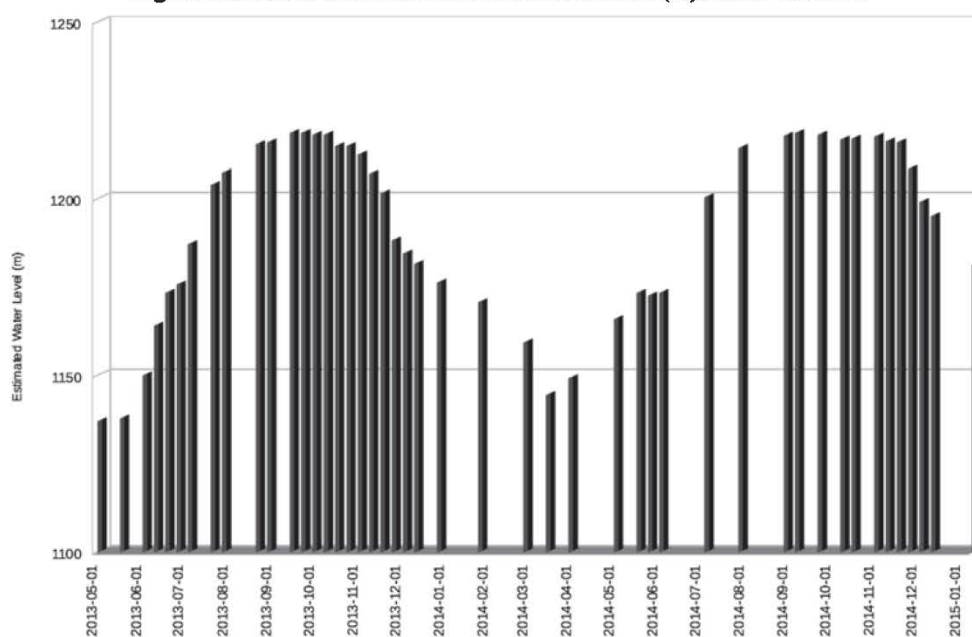


Figure 10: Mangla dam reconstructed water levels (m) from Landsat 8

### 3. Discussion and Conclusion

We studied the correlation between observed water levels used locally and the distance on the tracks of the wLVGs. We found that correlations hold strong in low slope flat upstream areas where water lines are well spaced thus clearly identified. The use of multiple wLVGs permits cross-checking of results, an alarm flag is risen when one (or more) wLVG result differs significantly from any other. This is mostly due to cloud noise, several wLVGs permit to still have a result by the majority rule, and then the

highest correlated value wLVG is reported as the best answer. When the wLVG is cloud covered, it does not report a convergence. A smaller water body (~2.5 Km<sup>2</sup>) without low slopes upstream did not find adequate linear correlation, however larger or equivalent water bodies with low slopes give results that are adequate and robust. Mostly we found linear relationships, but for lake Argyle, which is a very large water body and has a mixed material resistance because of its underlying sedimentary geology, we found that two or three

linear relationships can be defined with different water level ranges (Figure 3). For reservoirs with mixed geomorphology in upstream areas, regular linear low slope should be preferred, and wLVGs showing good fitting but not strictly aligned samples should be discarded under the suspicion of geomorphological non-linearity as found in wLVG3 of Mangla dam. An operational RMSE is found to be 12-52 cm height in some Sri Lankan tanks, depending on the characteristics of the upstream slopes used to calibrate wLVGs. This methodology is simple enough to be implemented for all medium to large reservoirs, we successfully worked on ~10, ~250 and ~700 Km<sup>2</sup> water bodies, including rural reservoirs in tropical/sub-tropical countries. Normalized un-calibrated changes in wLVGs have already been used 'in-house' to create baseline information for our own water resources research. Calibration to observed water levels can be done from the most local basic measures taken by local users, up to most advanced technology like Lidar or space altimetry. We would like to recommend the operationalization of this technique for local, crowd-sourced monitoring of smaller reservoirs, which are less in the national monitoring perspective. A relative (and/or normalized) baseline record can be generated from scratch by an experienced operator within 2 hours for any location on Earth. This has direct application for war-stricken areas where no records were taken for some years. A direct example is Iranamadu reservoir in North Sri Lanka. The interesting thing about this operationalised method is that the baseline records can be calibrated with actual measurements and be propagated back in time. On a more global perspective, countries withholding water storage information can be made available publicly within no time and monitored for transboundary negotiations, humanitarian rapid-response, or global environmental agreements. Finally, we anticipate that this can open globally distributed pathways to monitor open water bodies across the world, improve public databases on water storages and give management information for non/less-monitored water bodies.

#### Acknowledgements

The authors would like to thank the Irrigation Department office of Anuradhapura (Sri Lanka) as they provided the daily water level data for the purpose of this study. Dr. M. Edraki from the Bureau of Meteorology (Australia; [www.bom.gov.au](http://www.bom.gov.au)) is acknowledged for his help in gathering the water levels of Lake Argyle used in this study. The authors also acknowledge Water and Power Development Authority (WAPDA), Pakistan

for providing monsoonal water level data for Tarbela and Mangla reservoirs.

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