Physical Oceanography Distributed Active Archive Center (PO.DAAC)

Global Storage Change Time Series Data Set - Water Storage (MEaSUREs Project)

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User's Handbook
Version 2.0

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1. Introduction

The Global Storage Change Time Series Data Set were estimated using both The Global Optical Lake Area (GOLA) surface area data derived from MODIS and G-REALM (Global Reservoirs and Lakes Monitoring) Time Series Data Set for height data of lakes and reservoirs. Using methods derived from Gao (et al., 2012) storage capacity was calculated through a combination of direct observations of surface water height derived from altimetry data in addition to estimated surface area using classified MODIS data. Elevation-area relationships were derived from these data for each lake/reservoir, allowing us to create model based volume estimates for those with high correlations. These time series potentially span a 26 year time period, from late 1992 to 2018, satisfying the project goal of ESDR creation with a suitable level of quality that supports long-term trend analysis and global water dynamics models. This product is readily accessible and is of direct use to both water managers and the scientific community worldwide, and allows for improved assessment and modeling of the human impact on the global water cycle.

2. Methodology

2.1 Lake Locations

In order to estimate the surface area of the target, a static spatial extent is required as one of the inputs. We defined the initial spatial extents of water bodies using the vector polygons available as part of the Global Reservoir and Dam database (GRanD; Lehner et al., 2011) and Global Lakes and Wetlands Database (GLWD; Lehner and Döll, 2004), with quality checks ensured by visual comparison with high resolution satellite imagery (i.e., Google Earth, ESRI World Map) and Global Surface Water Explorer (Pekel et al., 2016). Whenever we identified a mismatch (i.e., polygon spatial extent not overlapping properly with the satellite imagery due to inaccurate georeferencing), the polygon was edited to match the expected location. In case a lake was not available as part of either database, a polygon was drawn by hand using high resolution imagery from various sources (e.g., Google Earth, ESRI World Map). Once correctly identified, these locations were used to construct a mask for altimetry and MODIS data extraction and create the WSE and GOLA products.

2.2 Storage Change Modelling

During time periods when both WSEs from G-REALM (supplemented with DAHITI and data from the Hydroweb database from LEGOS) and surface areas from GOLA were available, we derived the elevation-surface area relationships (i.e., hypsometry) for each target (Schwatke et al., 2015, Crétaux et al., 2011). We then used these relationships to estimate reservoir ΔV using an approach similar to Gao et al. (2012). Specifically, for overlapping G-REALM and GOLA periods, we calculated increments of volume for the corresponding changes in water elevation and surface area as:

$$\Delta V = (A_{t+1} + A_t)(h_{t+1} + h_t)/2, \quad (1)$$

where A_t and h_t are surface area and elevation at the smallest step t, and A_{t+1} and h_{t+1} are surface area and elevation at the next incremental step t+1.

We used linear regression to approximate the relationship between elevation (h) and surface area (A), $A = f(h)$. We then applied this relationship to estimate surface area from elevation for periods when surface area is unavailable (1992-1999), and the inverse function $h = f^{-1}(A)$ to estimate elevation from surface area for periods when elevation is unavailable during the MODIS era. Finally, the ΔV equation can be simplified into a single variable function, either as a function of elevation or GOLA surface area, by substituting $A = f(h)$ or $h = f^{-1}(A)$ into it. If the correlation coefficient between the two variables was smaller than 0.7 (i.e., weak to moderate correlation between WSE and surface area) and the variance of either variable was smaller than 2% (i.e., near-invariant variable), then we parameterized the invariant variable using its mean value.

The mask was then used to extract all of the data from three MODIS products whose nominal footprint overlapped the polygon of the corresponding lake. Specifically, we used: (i) two multispectral reflectance data products from the MODIS instruments onboard NASA's Terra and Aqua satellites as an input to the water/land classification algorithm (Collection 5 MCD43A4 and MOD0911), and (ii) static water and land classification labels to train the classification model (MODIS MOD44W). All MODIS data used to create the GOLA records are publicly available via the U.S. Geological Survey (USGS) Land Processes Distributed Active Archive Center (LP DAAC; http://lpdaac.usgs.gov), and a more detailed description of the classification algorithm can be found in Khandelwal et al. (2017).

2.3 Hypsometry Outlier Calculation

The first step in examining the relationship between water area and elevation time series was to see if there is any correlation between them. For that, we built two-variable arrays for each lake, temporal boundaries of which were defined as first and last date with both variables available. However, since both water extent and water height measurements have highly variable temporal resolution, when paired, only a few data points were left for the further analysis. In order to increase the pool of data points for the correlation analysis, we allowed a nearest neighbor interpolation, with the assumption that no spatial difference would occur within 8-day period (MODIS-derived time step). The resultant data set covered only a portion of the time extent for which either of the variables existed, and for which we attempted to estimate relative storage change. We also want to highlight that the elevation array, in many cases, is presented as a composition of altimeter data acquired from different sources (G-REALM, DAHITI, LEGOS HydroWeb). That made our water elevation arrays have irregular time steps. The following figure illustrates what portions of existing data have been used to run regression analysis and build a hypsometry equation (Figure 1).

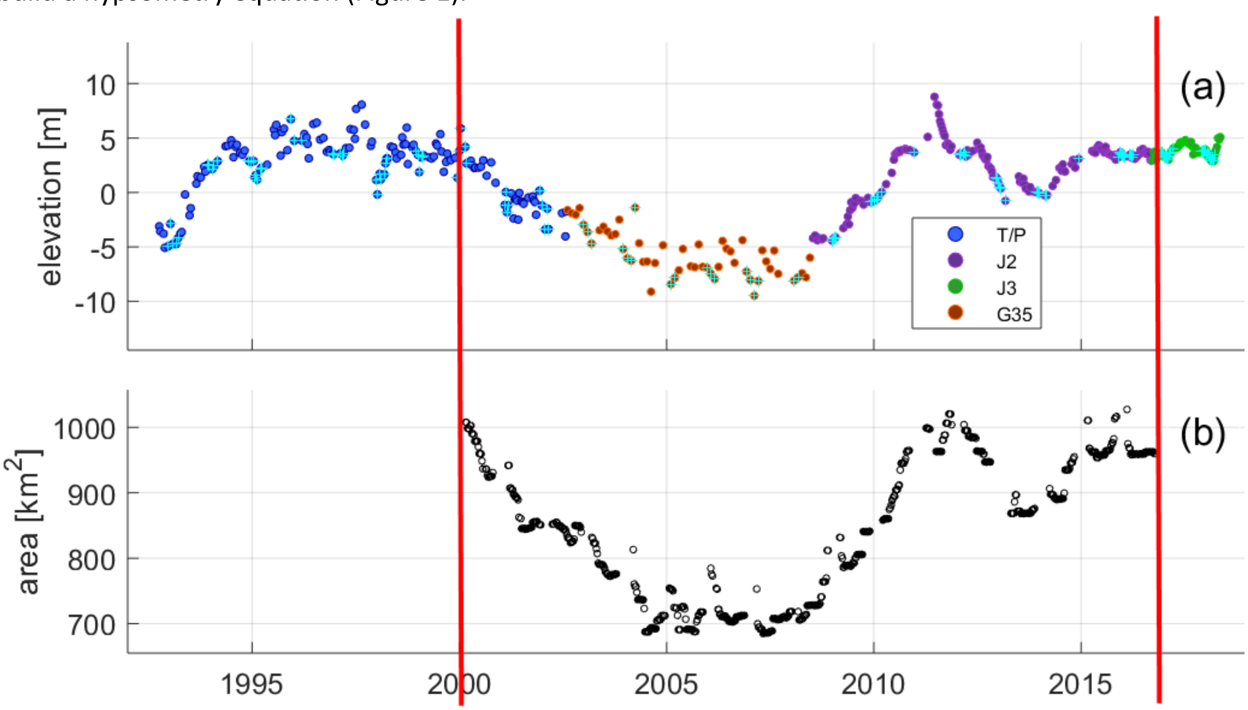

Figure 1. (a) Water height composite. The highest correlation was achieved with the altimeter data provided by G-REALM. Data collected by different missions is shown in different colors. Missing Jason-1 period is filled with G-REALM35 points. Data collected during known snow/ice event is shown with cyan cross symbol; (b) Water spatial extent. Only data points located inside the red boundaries were used for regression analysis.

We then thoroughly examined the relationship, testing for unreliable data, in order to achieve the highest correlation and derive the most accurate hypsometry. Building hypsometry was a three-step process: first, water elevation was plotted against area and a Pearson correlation coefficient was calculated. The correlation coefficient was the first measure of data potential to get reliable estimates of storage dynamics: the higher the coefficient value the stronger the confidence in using one variable to estimate another (e.g. using water elevation to estimate height, or vice versa). The initial plot gave an idea of ways to improve correlation by removing extraneous or unreliable data points. Second, for lakes that were known to experience freezing during winter months, and the months of "ice-on" and "ice-off" were defined, and corresponding data points within these dates removed. We then identified outliers using Grubbs test of ordinary least square regression. In the third and final step these outliers were removed. The results of the regression were further used to estimate values of elevation and area for dates when only one of them was available in-situ (Figure 2). In many cases, the correlation coefficient was increased when winter data and outliers were removed.

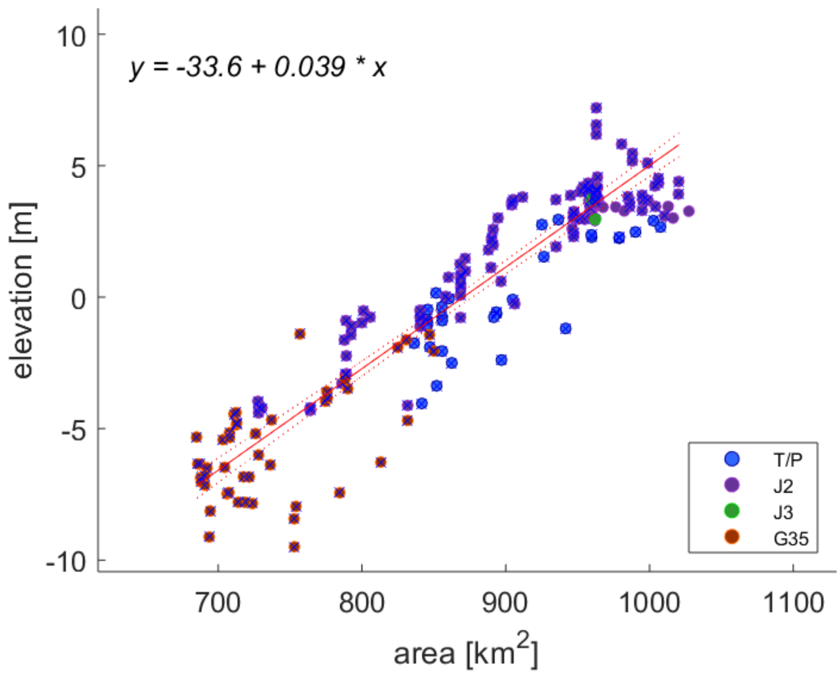

Figure 2. Hypsometry.

The hypsometry equation allowed us to estimate water area and water height data points to supplement their counterparts in the area-height time array. That step completed both variables with the time span that starts and ends with actual minimum and maximum time of existing measurement, whether it was water extent or water height, and with time-steps that represented either of the observations (Figure 3.).

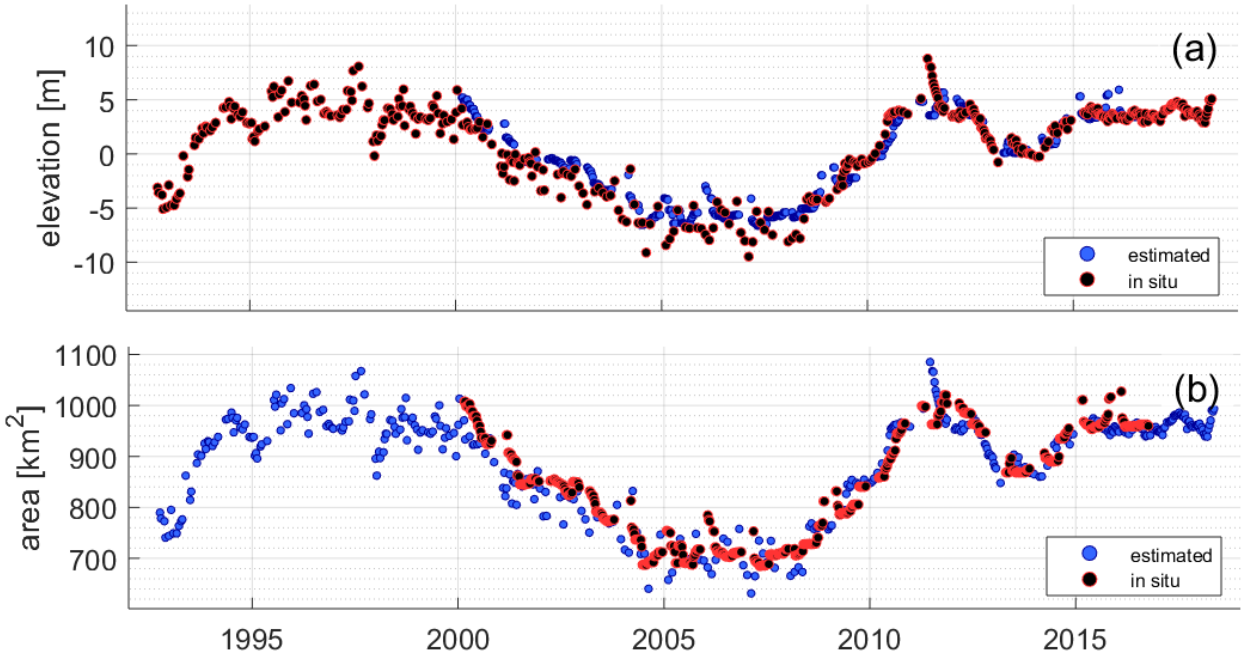

Figure 3. Estimated and in-situ: (a) water height and (b) water extent.

With the two-variable array completed, we calculated relative storage change for each lake as described in Gao, et al. (2012). The storage was estimated relative to the maximum value observed in the hypsometry data set. Thus, maximum storage is shown at zero level, in most cases. This explains why storage is negative for some lakes. In other cases, where, for example, a lake experienced a severe flooding event before 2002 or a drought after 2002 (earliest MODIS data available), the mean for variables in and outside the hypsometry region is considerably different. That would result in storage values exceeding our hypothetical zero maximum.

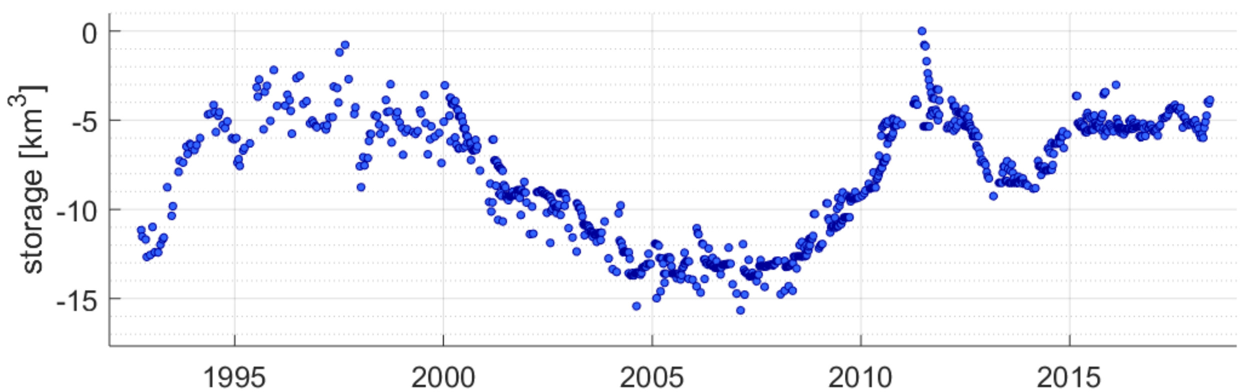

Figure 4. Estimated relative storage change.

2.4 MODIS Reflectance Data

The primary reflectance product was the bidirectional reflectance distribution function (BRDF) adjusted MCD43A4 16-day composite product. The MCD43A4 product is generated by the USGS using data from both the Terra and Aqua satellites to assure that the combined data product is of the highest possible quality. However, by ignoring poor data quality pixels, the MCD43A4 product suffers from a high degree of missing values, especially before Aqua data became available in 2002. This can introduce a high degree of incompleteness in classification maps. To alleviate this issue, we also used the MOD09A1 eight-day composite product collected solely from the Terra satellite. Since the MOD09A1 product is generally less reliable than MCD43A4 as it is not BRDF-adjusted, we combined these two products to compensate for the primary limitations of each, in addition to noise and missing values (cfr. Khandelwal et al., 2017). We also used quality flags to filter out pixels with snow, ice, or clouds. For the MOD10A1 product, information about the data quality is available along with the multispectral values in the 16-bit quality assessment state flags, whereas the quality flags for the MCD43A4 product are available as a separate product (MCD43A2 BRDF/Albedo Quality Product).

2.5 MODIS Land/Water Mask

In order to distinguish between land and water bodies, we used static water extent masks derived from the MODIS MOD44W product (Carroll et al., 2009) to train the supervised classification models. This product, distributed publicly by the USGS, combines MODIS 250 m reflectance data with the SRTM Water Body Dataset from 60°N to 60°S, with reflectance data used solely poleward of 60°N. We aggregated the MOD44W product from 250 m to 500 m to match the resolution of the other MODIS products. In particular, if the 500 m pixel had all of its four pixels at 250 m labeled as water or land in the MOD44W product, then we considered the pixel as a water or land pixel. We excluded partial pixels from the training set pool.

2.6 Ice Cover Assessment

Though frozen lake areas are a part of the unprocessed MODIS data product, they do not appear in the time series.

2.7 Validation

As described in Khandelwal et al. (2017), we have evaluated the performance of the approach on a global set of reservoirs comparing temporal variations in the surface extent maps with changes in relative water level height from satellite altimetry observations. Furthermore, *in situ* observations and higher resolution Landsat-based reference maps for isolated time steps were used for comparison with the MODIS-estimated area for five case studies.

3. Data Packaging and Variable Identification

3.1 Sample Surface Area Data (NetCDF format)

Format: netcdf4
Title = '[*continent*]_[*name*]_WaterAreaV2_[*id*].nc'
Example: 'South_America_AguaVermelha_WaterAreaV2_448.nc'

3.2 Variables

variable	dimension	datatype	units	long_name
surface_water_height	time	double	m	surface_water_height_time_series
surface_water_extent	time	float	m^2	surface_water_extent_time_series
water_storage	time	float	m^3	surface_water_storage_time_series
altimeter_source	time	double	1	altimeter_source_flag
ice_flag	time	double	1	ice_flag
outlier_flag_hypsometry	time	double	1	outlier_flag_hypsometry
outlier_flag_surface_area	time	double	1	outlier_flag_surface_area

model_flag	time	double	1	model_flag

3.3 Dimensions

dimension	axis	datatype	units	long_name
time	T	double	days since 1900-01-01T00:00:00	time

3.4 Global Attributes

attribute	comment	example
title	Title for the data in the file	Global Lake/Reservoir Storage Time Series Data for Lake Agua Vermelha
summary	Summary or abstract for the data in the file	The Global Lake/Reservoir Storage Time Series is derived from the Surface Water Height Time Series and Surface Water Extent Mask Time Series products. The purpose of this dataset is to provide surface water storage estimates for several hundred lakes and reservoirs across the globe. These time series potentially span a 26 year time period, from late 1992 to 2018, satisfying the project goal of ESDR creation with a suitable level of quality that supports long-term trend analysis and global water dynamics models. This product is readily accessible and is of direct use to both water managers and the scientific community worldwide, and allows for improved assessment and modeling of the human impact on the global water cycle.
keywords	A comma separated list of keywords	TERRESTRIAL HYDROSPHERE, SURFACE WATER PROCESSES/MEASUREMENTS, LAKES/RESERVOIRS, HYDROLOGIC AND TERRESTRIAL WATER CYCLE MODELS, POSEIDON-2, POSEIDON-3, POSEIDON-3b, Jason-class Altimeter, ALT (TOPEX), MODIS, MEaSUREs
conventions	A comma separated list of conventions	CF-1.7
doi	Digital object identifier	10.5067/UCLRS-GREV2
uuid	Unique identifier for data set	12c562cc-a333-11e9-bca8-a93c32dfccb5
history	An audit trail for modifications to the original data	Continuing efforts have been made to improve the quality of storage estimations from previous versions including: improvements on L3 buffer algorithm (see L3 product history) and modeling and inclusion of ice flag, identification of data outliers, identification of modeled data, and identification of altimetry source on both L2 (see L2 product history) and L4.
source	The method of production of the original data	MEaSUREs UCLA toolbox 2018
processing_level	Description of the processing or quality control level of the data	L4
comment	Useful additional information	Using methods derived from Gao (et al., 2012) storage capacity was calculated through a combination of direct observations of surface water height derived from altimetry data in addition to estimated surface area using classified MODIS data. Elevation-area relationships were derived from these data for each lake/reservoir, allowing us to create model based volume estimates for those with high correlations.
standard_name_vocabulary	CF standard name vocabulary	CF Standard Name Table v27

product_version	Version identifier of the data file or product as assigned by the data creator.	Version 2.0
date_created	Creation date of this version of the data (netCDF)	2019-01-11T01:52:00 AM
creator_name	Name of the person (or creator type) principally responsible for creating this data	MEaSUREs Team (Lettenmaier D., Noujdina N., Tortini R., Yeo S.)
creator_email	Email address of the person (or creator type) principally responsible for creating this data	dlettenm@ucla.edu (Lettenmaier D.), nnoujdina@ucla.edu (Noujdina N.), rtortini@ucla.edu (Tortini R.), samyeo@ucla.edu (Yeo S.)
creator_type	Specifies type of creator	Group
institution	Name of the institution primarily responsible for originating this data	University of California Los Angeles, Department of Geography
creator_institution	The institution of the creator	Land Surface Hydrology Research Group, UCLA
creator_url	The URL of the of the entity principally responsible for creating this data.	http://hydro.ucla.edu/
project		MEaSUREs UCLA
program	The overarching program(s) of which the dataset is a part.	NASA Earth Science Data Systems (ESDS)
publisher_name	The name of the entity responsible for publishing the data file or product to users.	PO.DAAC (Physical Oceanography Distributed Active Archive Center)
publisher_email	The email address of the entity responsible for publishing the data file or product to users.	podaac@podaac.jpl.nasa.gov
publisher_url	The URL of the entity responsible for publishing the data file or product to user.	podaac.jpl.nasa.gov
publisher_type	Specifies type of publisher	Institution
publisher_institution	The institution that presented the data file or equivalent product to users.	PO.DAAC
geospatial_lat_min	Describes a simple lower latitude limit	-20.2186955829839
geospatial_lat_max	Describes a simple upper latitude limit	-19.656195845917
geospatial_lon_min	Describes a simple lower longitude limit	-50.3662515859588
geospatial_lon_max	Describes a simple upper longitude limit	-49.1362437634452
geospatial_lat_units	Units for the latitude axis	degrees_north
geospatial_lon_units	Units for the longitude axis	degrees_east

geospatial_lon_resolution	Information about the targeted spacing of points in longitude	500 meters
geospatial_lat_resolution	Information about the targeted spacing of points in latitude	500 meters
time_coverage_start	Describes the time of the first data point in the data set	2000-02-18T00:00:00
time_coverage_end	Describes the time of the last data point in the data set	2016-10-15T00:00:00
keywords_vocabulary	Identifies the controlled keyword vocabulary used to specify the values within the attribute "keywords"	Global Change Master Directory (GCMD)
platform	Name of the platform(s) that supported the sensor data used to create this data set or product	TOPEX/Poseidon, Jason-1, Jason-2, Jason-3 (L2), TERRA/AQUA (L3)
platform_vocabulary	Controlled vocabulary for the names used in the "platform" attribute	NASA/GCMD Platform Keywords. Version 8.6
instrument	Name of the contributing instrument(s) or sensor(s) used to create this data set or product	TOPEX, Poseidon-2, Poseidon-3, Poseidon-3b (L2), MODIS (L3)
instrument_vocabulary	Controlled vocabulary for the names used in the "instrument" attribute	NASA/GCMD Instrument Keywords. Version 8.6
cdm_data_type	The data type	Grid
references	Published or web-based references that describe the data or methods used to produce it	Khandelwal et al. (2017). An approach for global monitoring of surface water extent variations using MODIS data. Remote Sensing of Environment, 202, 113-128

4. References

Carroll, M.L., J.R. Townshend, C.M. DiMiceli, P. Noojipady, and R.A. Sohlberg (2009). A New Global Raster Water Mask at 250 m Resolution. International Journal of Digital Earth, 2, 291-308.

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Appendix I: Coverage

Pearson's correlation coefficient was used to examine the relationship between lake area and water height variation. Higher correlation indicates a stronger relationship between the two variables.

Africa (n = 48)

ID	Lake	Correlation	R^2	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)
1431	Sterkfontein	0.049264	0.002427	0.466	-1435722844	0
1439	Shiroro	0.984392	0.969027	0.000	-5621210305	658524619.4
81	Chiuta	0.483110	0.233395	0.000	-799438776.6	0
82	Rukwa	0.942445	0.888202	0.000	-26250733359	5339911931
91	Naivasha	0.867358	0.752310	0.000	-633137997.6	0
93	Turkana	0.934076	0.872499	0.000	-34645326073	1800088714
314	Owen Falls	0.568359	0.323032	0.000	-150072000000	16007638276
315	Tanganyika	0.359840	0.129485	0.000	-69721500196	11456584539
317	Malawi	0.726641	0.528007	0.000	-91441684952	0
331	Nasser	0.978732	0.957916	0.000	-56245485837	4326919133
393	Volta	0.984517	0.969274	0.000	-79470146494	0
394	Kariba	0.983932	0.968121	0.000	-55703351446	0
398	Kyoga	0.575830	0.331580	0.000	-6221003750	249123733
402	Tana	0.924253	0.854244	0.000	-14883065920	0
414	Cahora Bassa	0.920766	0.847810	0.000	-33970983816	0
416	Mweru	0.217380	0.047254	0.000	-15234283523	2897011293
417	Kainji	0.910942	0.829816	0.000	-15055055849	0
553	Mai-Ndombe	0.254380	0.064709	0.002	-8894790403	0
554	Tumba	0.468451	0.219446	0.000	-3712727130	0
1499	Lagdo	0.857930	0.736044	0.000	-5464952790	0
1432	Cyohoha-sud	-0.152630	0.023296	0.214	-100076110.1	0
66	Iro	0.469011	0.219971	0.000	-510662670.2	0
74	Kisale	0.435348	0.189528	0.000	-1348140874	0
76	Sibayi	0.725125	0.525807	0.000	-1037373167	0
88	Nakuwa	0.031899	0.001018	0.784	-432543199.6	0
99	Shala	0.212212	0.045034	0.090	-6276401771	0

542	Tiga	0.902701	0.814869	0.000	-1155434256	108014351.7
546	Kossou	0.879585	0.773671	0.000	-4679546191	0
564	Mweru Wantipa	0.649538	0.421900	0.000	-10816708978	0
580	Vaaldam	0.969997	0.940894	0.000	-1999089981	0
4	Edward	0.753845	0.568282	0.000	-10300146766	0
11	Bangweulu	0.582714	0.339556	0.000	-7583362044	0
69	Kivu	0.150522	0.022657	0.072	-3623551902	166581490.6
403	Er Rosieres	0.946076	0.895059	0.000	-8035155173	0
405	Albert	0.629524	0.396300	0.000	-11046491749	0
535	Selingue	0.899168	0.808502	0.000	-2569518181	666788105.8
543	Yardi	0.785432	0.616904	0.000	-278819511.5	0
574	Massinger Barragen	0.979546	0.959510	0.000	-2119217564	0
1471	Buyo	0.848212	0.719464	0.000	-5121780850	0
73	Upemba	0.277281	0.076885	0.013	-1129319563	0
1547	ItezhiTezhi	0.983606	0.967481	0	-3390139335	158799739
1437	JebelAulia	0.858776	0.737495	0	-2304743172	0
85	Eyasi	0.139517	0.019465	0.242464	-10782944058	0
97	Abaya	0.403442	0.162766	0.013284	-3033839751	61483257.78
79	Chilwa	0.687481	0.47263	0	-4886999496	2980616575
60	Qarun	0.945	0.892543	0	-20998687693	0
67	Fitri	0.492072	0.242135	0.000031	-681383162.5	0
87	Ihema	0.262202	0.06875	0.25088	-7648054822	0

Asia (n = 119)

ID	Lake	Correlation	R^2	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)
177	Orba	-0.122342	0.014968	0.484	-614854592.7	0
285	Ngoring	0.969186	0.939322	0.000	-3131934534	0
434	Vilyui	0.603570	0.364296	0.000	-18988279344	0
1534	Mosul	0.931986	0.868597	0.000	-8871690283	380364081.1
121	Pangong	0.024770	0.000614	0.793	-1931143249	103393188.7
189	Dogai Coring	0.805844	0.649385	0.000	-4505266604	0
433	Ust Ilim	-0.206494	0.042640	0.032	-4350520468	682161122.4

479	Kayrakkum	0.937961	0.879771	0.000	-4078706622	208865593.1
519	Gandhi Sagar	0.988936	0.977994	0.000	-6993612221	0
583	Bratskoye	0.788543	0.621801	0.000	-44721732663	0
610	Sarykamyshskoye	0.954568	0.911199	0.000	-30077866936	2257187398
612	Toktogulskoye	0.971724	0.944247	0.000	-15782655618	0
615	Zaysan	0.848649	0.720206	0.000	-29530961638	0
625	Tarbela	0.958565	0.918846	0.000	-15679517145	0
652	Zhelin	0.083914	0.007041	0.243	-1477323249	13467442.85
166	Dogen	0.251821	0.063414	0.010	-466115633.6	0
152	Cha-jih nan-mu-tso	0.125523	0.015756	0.060	-3866073816	657343962.9
156	Ang-tzu	0.951346	0.905060	0.000	-5584981221	0
424	Aydar Kol	0.742048	0.550635	0.000	-25788625900	0
425	Krasnoyarskoye	0.800690	0.641104	0.000	-58631942391	0
459	Sayano Shushenskaya	0.964747	0.930737	0.000	-16053375070	0
958	Vallabhsagar	0.970811	0.942474	0.000	-5525126366	0
1378	Novosibirskoye	0.123723	0.015307	0.164	-7820804461	0
1450	Karakaya	0.891486	0.794746	0.000	-5533158996	0
1533	Fengman	0.748087	0.559634	0.000	-5515273482	0
1619	Three Gorges	0.777957	0.605216	0.000	-27802693175	0
1723	Bansagar	0.986149	0.972490	0.000	-6155959055	0
1947	Boguchany	0.991016	0.982112	0.000	-68032936989	0
1986	Ertan	0.840822	0.706981	0.000	-1844631970	282117065.4
4033	Zhexi	0.426670	0.182047	0.000	-990879986.1	55122295.89
972	Lam Pao	0.923607	0.853050	0.000	-1310098714	0
1500	Srisailam	0.958790	0.919278	0.000	-4029182521	446840593.6
2282	Xiaolangdi	0.844288	0.712822	0.000	-6769912190	980434755.6
4034	Tehri	0.770302	0.593366	0.000	-3030987589	0
111	Ercek	-0.178504	0.031864	0.012	-299668924.7	42983252.29
3849	Jabbul (1)	0.374629	0.140347	0.000	-361396459.3	0
107	Beysehir	0.589326	0.347305	0.000	-2498401367	0
115	Urmia (1)	0.358411	0.128459	0.000	-19991898594	9126779498
141	La-ang	0.171802	0.029516	0.014	-3422747304	0

209	Ulungar	0.548986	0.301385	0.000	-2577038420	554779104.2
224	Khanka	0.598068	0.357685	0.000	-60393516725	0
232	Chany	0.019867	0.000395	0.801	-4680501370	0
234	Sasykkol	0.213949	0.045774	0.001	-1675598313	196515692.1
238	Zhalauly	-0.017944	0.000322	0.833	-174916516.3	0
269	Buhayrat ath Tharthar	0.967230	0.935533	0.000	-25650152943	16378653930
275	Kara-Bogaz-Gol	0.559517	0.313059	0.000	-115023000000	1601479080
277	Aral (2)	0.936784	0.877565	0.000	-56775569390	9027476633
278	Balkhash	0.605036	0.366069	0.000	-73021924152	0
316	Baikal	0.500579	0.250580	0.000	-128745000000	0
319	Boeng Tonle Chhma	0.933699	0.871794	0.000	-43276651760	0
338	Issyk-kul	-0.018781	0.000353	0.657	-8288368241	0
343	Sanhezha	0.457274	0.209099	0.000	-8251082311	818994612.7
347	Bosten	0.855195	0.731358	0.000	-5563533716	0
353	Zeyaskoye	0.899617	0.809310	0.000	-39011863512	0
372	Dorgon	0.865427	0.748964	0.000	-785609793	343345152.4
385	Hulun	0.968032	0.937086	0.000	-9597728815	1201567244
411	Har Nuur	0.404705	0.163786	0.000	-2839246587	0
413	Hovs Gol	0.100670	0.010134	0.258	-7905501240	0
431	Kapchagayskoye	0.801985	0.643180	0.000	-6881608703	0
449	Gaoyou	0.128885	0.016611	0.027	-5143632439	0
460	Chardarinskoye	0.970040	0.940977	0.000	-5859558023	0
587	Chukchagirskoye	-0.210655	0.044376	0.008	-1023368261	0
1442	Aral (3)	0.941070	0.885612	0.000	-11989114427	0
963	Nagarjuna Sagar	0.311752	0.097189	0.000	-4320019560	0
1454	Ust Khantaika	0.617694	0.381545	0.002	-14032700681	0
2311	Farakka	0.886944	0.786669	0.000	-12475274394	0
828	Khantayskoye	0.578689	0.334881	0.024	-6033231470	0
140	Ma-pang yung-tso	0.051618	0.002664	0.693	-835377235.5	0
146	Ta-jo	0.549753	0.302229	0.002	-1836989213	0
155	Tang-je yung-tso	0.263920	0.069654	0.013	-6010979252	0
163	Na-Mu	0.762424	0.581290	0.000	-17605931116	0

179	Lumajangdong	0.779654	0.607861	0.000	-3018216456	16752574.68
185	Dagze	0.828679	0.686708	0.000	-1123207310	0
205	Ayakkum	0.932623	0.869785	0.000	-7151169592	0
388	Razazza	0.926709	0.858790	0.000	-4438692107	322083719.2
110	Tuz	-0.273333	0.074711	0.066	-3224190040	0
226	Barun-Torey	0.771637	0.595423	0.000	-2462370286	0
575	Markakol	0.275717	0.076020	0.268	-13513853502	0
609	Mingechaurskoye	0.637234	0.406067	0.000	-9199349747	0
628	Beas	0.968830	0.938632	0.000	-5723550047	0
632	Han Shui	0.863310	0.745305	0.000	-8215233397	0
639	Kasumiga-ura	-0.218918	0.047925	0.082	-848825524	0
645	Govind Ballabah Pant	0.838064	0.702352	0.000	-5622842741	0
646	Indawngy	0.214898	0.046181	0.074	-411703500.7	0
959	Ujjani	0.891472	0.794723	0.000	-2212400482	0
968	Bhumphol K. K. Nam	0.960501	0.922563	0.000	-6074669625	165053405.3
969	Sirikit	0.901976	0.813560	0.000	-6063020951	0
970	Nam Ngum	0.730346	0.533405	0.000	-7641749105	0
977	Srinagarind	0.721738	0.520906	0.000	-4603729129	0
1005	Senanayake Samudra	0.901759	0.813169	0.000	-673427472.8	0
112	Van	-0.266002	0.070757	0.003	-6204910752	0
158	Se-lin	0.981538	0.963417	0.000	-37913662832	0
201	Qinghai	0.944064	0.891257	0.000	-11080548914	0
217	Hyargas	0.874885	0.765424	0.000	-12412447948	1894500685
218	Uvs	0.450291	0.202762	0.000	-6191435536	0
260	Sevan	0.579533	0.335859	0.000	-5947610816	0
527	Bahrat Assad	0.128378	0.016481	0.242	-3042013173	52826353.66
653	Poyang	0.740086	0.547728	0.000	-19115393209	7183521149
661	Tai (1)	-0.022008	0.000484	0.876	-3447341710	0
1438	Ataturk	0.753845	0.568282	0.000	-10300146766	0
1457	Qadisiyah	0.962002	0.925448	0.000	-7878195830	0
387	Habbaniyah	0.949325	0.901217	0.000	-2197277061	0
525	Keban Baraji	0.800455	0.640729	0.000	-10447675406	576502071.4
526	Dukan	0.971123	0.943080	0.000	-5456265856	0

1577	Karkheh	0.866851	0.751430	0.000	-2870041406	0
1597	Batman Baraji	0.789366	0.623099	0.000	-1254130483	0
2314	Dez	0.454283	0.206373	0.000	-1784483037	0
2319	Adhaim	0.845535	0.714929	0.000	-687240565	0
2328	Hammar (1)	0.553965	0.306878	0.000	-111625862.7	1583016269
2329	Hammar (2)	0.193862	0.037583	0.141	-103246406.1	843290591.8
787	Kureiskaya	0.262202	0.06875	0.25088	-7648054822	0
496	Tungabhadra	0.937467	0.878844	0	-1634932646	0
2280	Thaphanseik	0.839917	0.705461	0	-1797202779	192239743
2315	Geheyan	0.13389	0.017927	0.48058	-950683831.3	0
1568	Wuqiangxi	0.450984	0.203386	0.004488	-696008635.1	0
1976	Dongjiang	-0.445	0.197635	0	-678830042.9	0
4286	Baishan	0.150317	0.022595	0.374529	-1094639254	0
1478	ThaleLuang	0.793556	0.629731	0	-1597159869	0
1712	Almatti	0.969113	0.939179	0	-3232792032	0

Europe (n = 31)

ID	Lake	Correlation	R^2	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)
435	Vygozero	-0.017200	0.000296	0.871	-1916780624	0
505	Paijanne	-0.242434	0.058774	0.045	-1136577780	149644257
600	Tshchikskoye	0.823858	0.678742	0.000	-2026132318	15269181.74
953	Beloye	-0.228386	0.052160	0.008	-1377991476	95033894.89
592	Tsimlyanskoye	0.845852	0.715465	0.000	-13505590339	121932812.1
809	Votkinskoye	-0.355306	0.126242	0.000	-7546007686	172233606.2
810	Kama	-0.171722	0.029488	0.019	-13011674157	260552941.6
1000	Sheksna	-0.298202	0.088924	0.006	-373207265.3	32122841.39
1341	Gorky	-0.153587	0.023589	0.075	-3195778891	56567293.7
1376	Kuybyshevskoye	0.378040	0.142914	0.000	-36896637259	0
1377	Volgograd	0.403434	0.162759	0.000	-6162146940	0
1462	Saratov Reservoir	-0.022901	0.000524	0.771	-2268771853	349323386.7
1618	Nizhne Kamskaya	0.592492	0.351047	0.000	-3176519625	0
590	Krasnooskolskoye	-0.121327	0.014720	0.081	-162953119.9	1467433.174

873	Kakhovskoye	-0.569832	0.324709	0.000	-3158215593	294766788.6
397	Saimmaa	-0.130798	0.017108	0.098	-6920010027	0
22	Onega	-0.155921	0.024311	0.023	-19316805588	98555130.55
26	Vanern	0.054377	0.002957	0.330	-10541192578	0
221	Peipus	0.246718	0.060870	0.000	-8377568792	0
223	Rybinskoye	0.906079	0.820979	0.000	-21521316780	0
340	Ijsselmeer	-0.260574	0.067899	0.000	-79394777.99	922364.0526
396	Ladoga	0.248888	0.061945	0.000	-53196050422	0
502	Sivash	0.301253	0.090754	0.000	-6411752050	0
503	Kremenshugskoye	0.295626	0.087395	0.000	-8269632253	0
520	Kiyevskoye	-0.209267	0.043793	0.007	-1217426469	0
851	Konstanz	-0.625631	0.391415	0.000	-1011246475	0
1451	Cheboksary	0.156366	0.024450	0.094	-3323352731	0
956	IlMen	0.870787	0.758271	0.000	-6758481829	0
601	Kiziltashskiy	0.259498	0.067339	0.028	-1076219393	0
356	Inarinjarvi	0.274	0.04574	0.176		
955	Kubenskoye	0.851	0.110754	0.000		

North America (n = 113)

ID	Lake	Correlation	R²	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)
118	Nettiling	0.047748	0.002280	0.764	-22120787474	321367372.5
222	Nipigon	0.010255	0.000105	0.886	-9205008715	0
236	Reindeer	0.529924	0.280819	0.000	-22932889886	0
244	Dubawnt	0.593265	0.351964	0.000	-12385167312	825677820.8
252	Cedar	0.788886	0.622341	0.000	-11215217176	0
264	Amadjuak	0.367267	0.134885	0.005	-11412833176	0
348	Athabasca	0.522279	0.272775	0.000	-26873329994	4900118926
408	Baker	0.174080	0.030304	0.063	-6352517256	0
410	Southern Indian	0.200315	0.040126	0.010	-14037291298	684617399.2
412	Martre	-0.057909	0.003353	0.559	-1864256679	0
420	Great Slave	-0.253921	0.064476	0.001	-48772848458	9754569692
421	Great Bear	0.015098	0.000228	0.857	-86767695068	0

423	Wollaston	0.056411	0.003182	0.499	-5046475565	239869149.4
436	Becharof	0.493913	0.243950	0.000	-1592989575	0
440	Aberdeen	0.382793	0.146531	0.003	-5152219419	0
443	Napaktuluk	0.733987	0.538737	0.007	-3537440335	0
498	Mallery	0.112917	0.012750	0.645	-955611505.1	85322455.82
254	Smallwood	0.727631	0.529447	0.000	-25118657125	2810838674
258	Iliama	0.514362	0.264568	0.000	-8262017739	0
409	Yathkyed	0.436903	0.190884	0.010	-6681625462	37189009.99
429	Kasba	0.298365	0.089022	0.002	-4073207032	26535550.7
453	Toledo Bend	0.595410	0.354513	0.000	-2084612982	0
470	Gods	0.359368	0.129145	0.000	-3737427544	182023871.8
706	Falcon	0.963785	0.928881	0.000	-3220285315	0
341	Angostura	0.983089	0.966464	0.000	-11055853511	0
441	Claire	0.511800	0.261940	0.000	-3096779711	544985261.1
442	Nueltin	0.444467	0.197551	0.000	-4673810992	0
475	Tehek	-0.314732	0.099056	0.006	-670984961.4	0
484	Dore	0.318017	0.101135	0.000	-1308320162	0
504	Manicouagan	0.145096	0.021053	0.286	-18141618127	0
512	Ear Falls	0.117553	0.013819	0.244	-3062225573	0
678	Bear (2)	0.789437	0.623210	0.000	-959493061.5	434406963.4
682	Fort Peck	0.953840	0.909811	0.000	-15661690949	0
684	Sakakawea	0.895312	0.801583	0.000	-17686231481	0
1025	Hardish	-0.170736	0.029151	0.088	-762150119.4	0
1031	Aylmer	-0.284051	0.080685	0.008	-2145191296	0
1053	Schultz	-0.179790	0.032324	0.207	-2637996726	0
1081	Keller	-0.152061	0.023122	0.090	-947090208.4	0
1118	Ford	0.331841	0.110118	0.010	-1316259232	122073115
1121	Carey	0.148403	0.022024	0.284	-644356590.2	37839903.85
1155	Williston	0.643844	0.414535	0.000	-38724962347	0
1238	Low	0.913937	0.835281	0.000	-5141180071	0
1240	Grande (1)	0.837929	0.702125	0.000	-12297984359	0
1241	La Grande (3)	0.907369	0.823318	0.000	-24079125271	502594814

1302	Champlain	0.213799	0.045710	0.000	-3230961721	0
1418	Hugh Keenleyside	0.511272	0.261399	0.000	-22888970021	0
1465	Oahe	0.962452	0.926314	0.000	-17541584324	0
1469	Baird Inlet	0.110244	0.012154	0.225	-1914441242	0
1490	La Grande (4)	0.761118	0.579300	0.000	-6178107107	0
1493	Grand Coulee	0.779088	0.606978	0.000	-7649751752	0
1516	Mica	0.652381	0.425601	0.000	-19905589080	0
1604	Bagnell	-0.242832	0.058968	0.001	-441844682.9	6793430.377
669	Libby	0.748747	0.560622	0.000	-13828847697	0
12	Winnipeg	-0.028157	0.000793	0.674	-67848865414	0
21	Windsor	0.426792	0.182151	0.000	-239868323.1	0
42	Manitoba	0.662992	0.439559	0.000	-15575161727	0
203	Winnipegosis	0.373733	0.139676	0.000	-18181112158	0
266	Woods	-0.245327	0.060185	0.000	-10475359607	0
333	Erie	-0.196855	0.038752	0.000	-27169707219	9832846422
334	Ontario	-0.567924	0.322537	0.000	-22552040599	8095604318
335	Michigan	0.012015	0.000144	0.821	-84952204137	18619661181
336	Huron	-0.036690	0.001346	0.510	-80931389396	22613182331
337	Superior	-0.167105	0.027924	0.002	-90318687020	18063737404
351	Nicaragua	0.577755	0.333801	0.000	-22529507472	0
368	Salton Sea	0.902522	0.814546	0.000	-3909806175	0
454	Lesser Slave	0.367726	0.135222	0.000	-2968501530	1057741924
462	Powell	0.914406	0.836139	0.000	-7447464998	946611246.3
480	Winnebago	-0.323241	0.104485	0.000	-1256187601	231238513.6
486	Yellowstone	-0.190991	0.036478	0.030	-1301327504	0
509	St. Jean	0.100591	0.010119	0.132	-4967170217	326926277.5
1161	Primrose	-0.070599	0.004984	0.374	-890103926.6	117807872.6
1168	Diefenbaker	0.832508	0.693069	0.000	-3446761171	0
1285	Dale Hollow	-0.341982	0.116952	0.000	-431713909.5	0
506	St. Claire	-0.184459	0.034025	0.113	-1457903068	0
1009	Teshekpuk	-0.582327	0.339105	0.130	-2696439977	0
1017	Colville	-0.573396	0.328783	0.005	-523244161.6	0

1019	Maunoir	-0.057525	0.003309	0.799	-697143068.7	0
1111	Kamilukuak	-0.051970	0.002701	0.774	-800546449.4	0
1112	Nowleye	-0.092378	0.008534	0.753	-504142531.8	0
1115	Tebesjuak	0.093004	0.008650	0.752	-951003944.5	0
721	Izabal	-0.164819	0.027165	0.176	-555812534.8	0
1247	Caniapiscau	0.836751	0.700152	0.000	-27944248251	0
14	Eagle (2)	0.134992	0.018223	0.371	-2266239871	0
28	Peten Itza	0.334724	0.112040	0.003	-1103212736	0
293	Adjuntas	0.852633	0.726984	0.000	-2337036962	1882598805
312	Walker (2)	0.727440	0.529169	0.000	-1297811179	52747656.2
665	Clear (2)	0.520203	0.270611	0.000	-550208598.3	0
701	Alvara Obregon	0.946431	0.895732	0.000	-4751494937	0
717	Miguel Aleman	0.938049	0.879936	0.000	-8729377167	0
1261	Livingston	0.252525	0.063769	0.028	-2574037189	0
1287	Hartwell	0.334724	0.112040	0.003	-1103212736	0
1289	Clark Hill	0.554538	0.307513	0.000	-1162633697	0
1290	Murray (2)	0.393992	0.155229	0.002	-1841734561	0
1291	Marion	0.097041	0.009417	0.424	-1724087040	0
19	Great Salt	0.570244	0.325179	0.000	-28316568489	1011852327
350	Managua	0.959562	0.920760	0.000	-7209110954	0
461	Mead	0.970600	0.942065	0.000	-19424108287	510406229.5
671	Flathead	0.021710	0.000471	0.846	-1674750772	0
715	Chapala	0.892120	0.795879	0.000	-7045142434	151035443.5
716	Infiernillo	0.943764	0.890690	0.000	-5406296774	0
720	Malpaso	0.856664	0.733872	0.000	-9359090091	0
1297	Okeechobee	0.503843	0.253857	0.000	-3586799156	0
468	Eufaula	0.318407	0.101383	0.000	-1394808878	0
680	Flaming Gorge	0.536883	0.288244	0.000	-951819144.1	39455826.11
1164	Montreal	-0.002003	0.000004	0.991	-752622128.8	0
1273	Denison	0.277281	0.076885	0.013	-1129319563	0
1278	Bull Shoals	0.484574	0.234812	0.000	-2436445516	0
1279	Table Rock	0.222687	0.049589	0.039	-789413717.7	0

1495	Kentucky	0.000098	0.000000	0.999	-1674086841	0
1602	Harry Truman	0.155049	0.024040	0.187	-962754635.6	0
1603	Blakely Mountain	0.238150	0.056715	0.031	-660586669.1	0
1861	Norris	-0.334382	0.111811	0.002	-582859659.7	74586895.16
1905	Hungry Horse	-0.534429	0.285614	0.001	-2294332922	0

South America (n = 53)

ID	Lake	Correlation	R^2	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)
448	Agua Vermelha	0.943831	0.890817	0.000	-4846989413	0
51	Poopo	0.877930	0.770761	0.000	-7230622430	0
345	Sobradino	0.963362	0.928067	0.000	-27635033509	0
744	Todos los Santos	0.264137	0.069768	0.000	-814946171.6	32234053.86
754	Viedma	0.283788	0.080536	0.000	-5951388242	0
794	Iepe	0.857314	0.734988	0.000	-4998233799	0
439	Colhue Huapi	0.888754	0.789884	0.000	-3594709998	0
753	Argentino	0.389209	0.151483	0.000	-7405533734	484493771.7
798	Promissao	0.240872	0.058019	0.001	-1737246000	60869285.83
1422	Itumbiara	0.922664	0.851308	0.000	-12279329469	0
1479	Sao Simao	0.856898	0.734275	0.000	-5436640640	0
1551	Salto Caxias	0.032820	0.001077	0.659	-1169295409	0
1554	Mascarenhas de Moraes	0.645771	0.417021	0.000	-1750100214	0
1621	Represa Nova Ponte	0.939113	0.881932	0.000	-9009957008	0
1778	Balbina	0.882377	0.778588	0.000	-10591133276	282662353.4
1419	Emborcacao	0.890412	0.792834	0.000	-12933443721	0
1617	La Vueltosa	0.852797	0.727263	0.000	-3098472283	0
53	Mangueira	0.651835	0.424889	0.000	-4347028931	0
344	Chiquita	0.916598	0.840151	0.000	-32707748270	0
432	Guri	0.971538	0.943887	0.000	-76828506660	566702372.4
501	Itaipu	0.401386	0.161110	0.000	-5106719464	696105693.6
741	Musters	0.420110	0.176493	0.000	-1201155436	0
748	Ranco	0.180780	0.032682	0.013	-1293507831	0
1420	Represa de Furnas	0.958655	0.919020	0.000	-14544086269	0

1460	Serra da Mesa	0.944745	0.892543	0.000	-20998687693	0
1548	Tres Irmaos	0.269835	0.072811	0.028	-2137817966	0
1669	Cupari	0.899726	0.809507	0.000	-20241287163	0
1670	Xingu	0.521567	0.272032	0.000	-4467907378	0
1546	Itaparica	0.512430	0.262585	0.000	-4761078524	0
1589	Iguazu	0.724245	0.524530	0.000	-2173385384	0
726	De Betania	0.570719	0.325720	0.000	-706154471.4	0
732	Rinihue	0.219717	0.048276	0.079	-768339880	0
776	Amana	0.899066	0.808319	0.000	-1272453604	210946526.3
777	Coari	0.859385	0.738542	0.000	-15181006238	0
779	Aiapua	0.818084	0.669261	0.000	-2545094273	0
780	Piorini	0.885714	0.784489	0.000	-4164525608	0
796	Barra Bonita	0.564456	0.318610	0.000	-3821576353	0
802	Juparana	-0.147975	0.021896	0.255	-955103090.2	0
808	Rincon-Bonete	0.898535	0.807366	0.000	-9520120041	0
1393	Poco da Cruz	0.861578	0.742317	0.000	-285085918	0
37	Buenos Aires	0.053596	0.002873	0.476	-6133775251	0
318	Titicaca	0.824425	0.679676	0.000	-25908216481	0
463	Repressa Tres Marias	0.960341	0.922254	0.000	-14231680579	0
745	Lianquihui	-0.088889	0.007901	0.197	-942885540.6	0
783	Taciula	0.868094	0.753587	0.000	-1882268595	0
785	Tucurui	0.983379	0.967035	0.000	-29581971214	0
793	Repressa de Jupia	0.714691	0.510783	0.000	-9405855191	992270894.4
43	Cardiel	-0.145132	0.021063	0.325	-798871624.4	0
773	Brokopondo	0.868114	0.753622	0.000	-8494882616	100178584.9
2309	RepresaDeSamuel	0.96	0.920931	0	-1043893628	0
1824	Yacyreta	0.981	0.962235	0	-14807754232	0
346	NahuelHuapi	0.012442	0.000155	0.839	-3101745630	0
1765	FuroSantaMaria	-0.533	0.284062	0	-2762542111	0

Oceania and Pacific (n = 8)

ID	Lake	Correlation	R^2	P-Value	Rel. Storage Min (m3)	Rel. Storage Max (m3)

511	Taupo	-0.236898	0.056121	0.000	-924775644.7	133849106.5
1440	Alexandrina	0.918434	0.843521	0.000	-2050096715	0
1470	Eildon	0.911572	0.830963	0.000	-2751285380	0
763	Eucumbene	0.927153	0.859613	0.000	-2561062149	0
998	Murray (1)	0.759249	0.576459	0.000	-2155355758	0
1413	George (4)	-0.295475	0.087305	0.219	-1766612780	0
755	Argyle	0.896348	0.803440	0.000	-11773925101	0
762	Hume	0.852298	0.726412	0.000	-1784112850	0

Appendix II: Notes and Errors Documentation

Lake ID	Lake Name	Error Type	Notes
2327	Aral (1)	Deleted	Waterbody removed from Version 2
270	Caspian	Deleted	Waterbody removed from Version 2
68	Chad	Deleted	Waterbody removed from Version 2
320	Eyre	Deleted	Waterbody removed from Version 2
415	Kafue	Deleted	Waterbody removed from Version 2
1286	Wolf Creek	Deleted	Waterbody removed from Version 2
332	Torrens	Deleted	Waterbody removed from Version 2
406	Kwania	Deleted	Merged with Kyoga (ID 398)

Appendix III: Acronyms

BRDF: Bidirectional Reflectance Distribution Function
CF: Climate and Forecast
DAHITI: Database for Hydrological Time Series of Inland Waters
ESDR: Earth System Data Records
ESDS: Earth Science Data System
ESRI: Environmental Systems Research Institute
G-REALM: Global Reservoir and Lake Monitor
GCMD: Global Change Master Directory
GLWD: Global Lakes and Wetlands Database
GOLA: Global Optical-derived Lake Area
GranD: Global Reservoir and Dam Database
Jason: Joint Altimetry Satellite Oceanography Network
L2: Level 2 - processing level for Time Series Data Set for Water Height (Altimetry)

L3: Level 3 - processing level for Time Series Data Set for Water Area (Surface Area)
L4: Level 4 - processing level for Time Series Data Set for Storage (Hypsometry)
LEGOS: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LP DAAC: Land Processes Distributed Active Archive Center
MEaSUREs: Making Earth Science Data Records for Use in Research Environments
MODIS: Moderate Resolution Imaging Spectroradiometer
NASA: National Aeronautics and Space Administration
NetCDF: Network Common Data Form
PO.DAAC: Physical Oceanography Distributed Active Archive Center
SRTM: Shuttle Radar Topography Mission
T/P: Topex/Poseidon
TOPEX: Topography Experiment of the ocean
UCLA: University of California, Los Angeles
USGS: United States Geological Survey
WSE: Water Surface Elevation