

**Collection 6 MODIS Global Reservoir Product User's Guide  
Version 1.0**

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**Document Change History Log**

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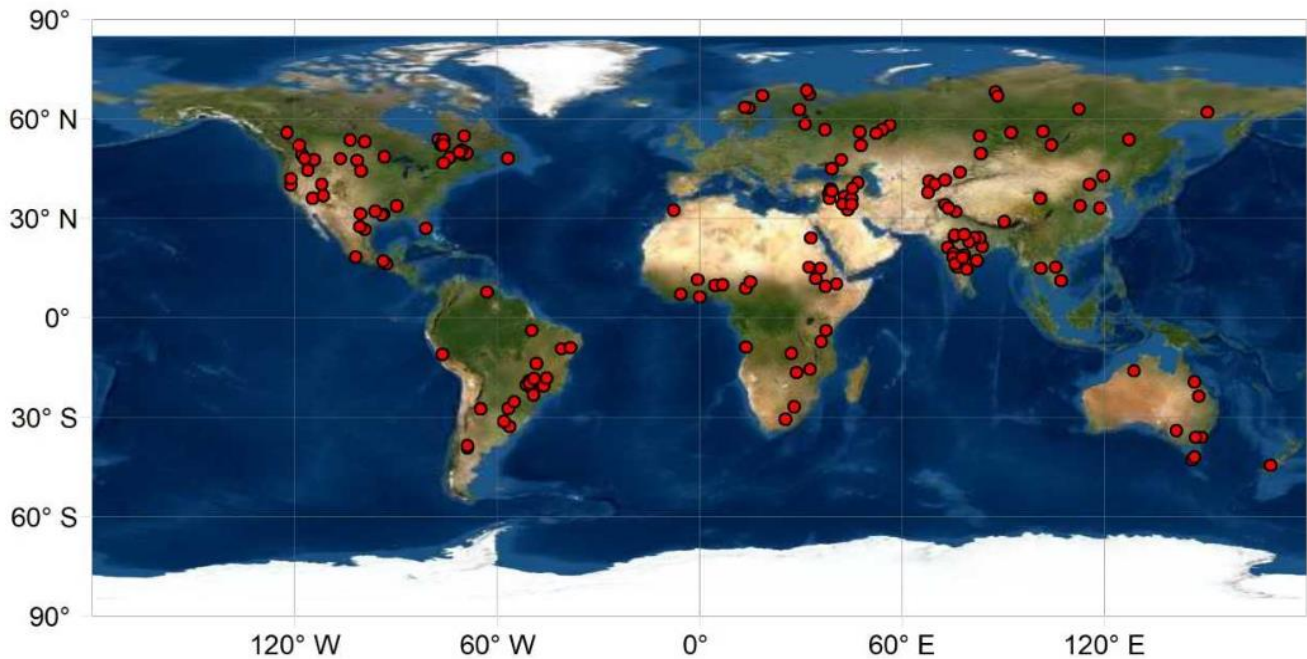
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### 1. Introduction

This document provides the most current information about the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 Global Water Reservoir product from both Terra (MOD28) and Aqua (MYD28) satellites. This product provides data for 164 reservoirs (Figure 1), which includes 151 man-made reservoirs (2,672 km<sup>3</sup>) and 13 regulated natural lakes (23,801 km<sup>3</sup>). The total storage capacity of the 151 man-made reservoirs represents 45.82% of the global capacity (in its category) according to the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011). More details about these reservoirs and their attributes are provided in Appendix A.

For each reservoir, the results (from both Terra and Aqua) are presented at two temporal resolutions: 8-day and monthly (Table 1). The surface area, elevation, and storage values are available at both 8-day and monthly; while the evaporation rate and volumetric evaporation are only available at monthly intervals. This document is intended to provide the end user with practical information about how to use these products.



**Figure 1.** Locations of the 164 global reservoirs contained in this product.

**Table 1.** Summary of the MxD28 Global Water Reservoir product

Terra/ Aqua Product ID	Temporal Resolution	Variables
MOD28C2/MYD28C2	8-day	Area, elevation, and storage
MOD28C3/MYD28C3	Monthly	Area, elevation, storage, evaporation rate, volumetric evaporation

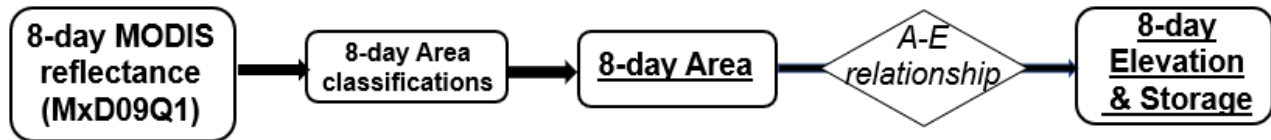
## 2. MODIS Reservoir Product (MxD28) Algorithm Summary

### 2.1 MxD28C2 Algorithm

Figure 2 shows the algorithm for generating the MxD28C2 8-day product, which is described in more detail in Li et al. (in preparation). First, the 8-day reservoir area values are extracted from the 250-m Near Infrared (NIR) bands of MODIS Terra/Aqua surface reflectance (MOD/MYD09Q1) data. During the classification process, an area enhancement algorithm (after Zhang et al., 2014) is adopted to minimize the effects of various sources of contamination (e.g., cloud and snow/ice). Then, the area values are applied to the Area-Elevation (A-E) relationship—provided by the Global Reservoir Bathymetry Dataset (GRBD, Li et al., 2020)—to calculate the corresponding elevation value. Lastly, the reservoir storage can be estimated using Equation (1) (after Gao et al., 2012):

$$V_{MODIS} = V_c - (A_c + A_{MODIS})(h_c - h_{MODIS})/2 \quad (1)$$

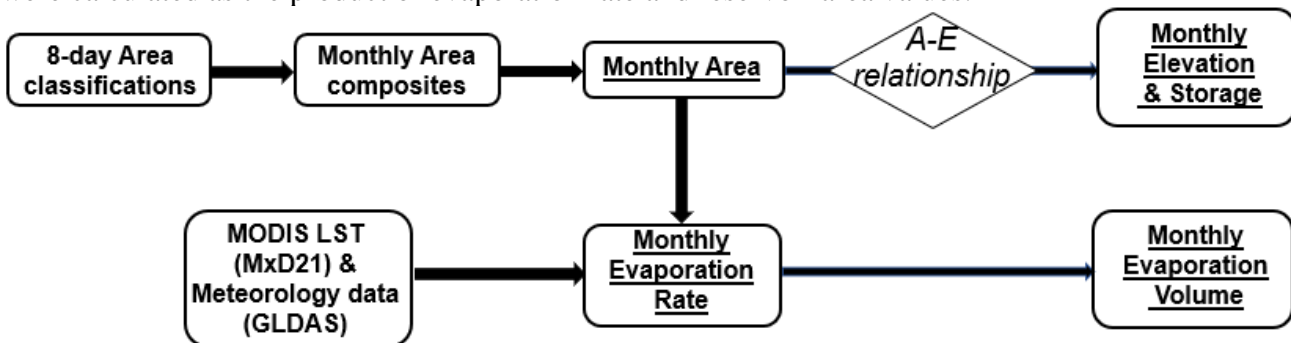
where  $V_c$ ,  $A_c$ , and  $h_c$  represent storage, area, and water elevation values at capacity; and  $V_{MODIS}$ ,  $A_{MODIS}$ , and  $h_{MODIS}$  are the estimated storage, area, and water elevation from MODIS.



**Figure 2.** Flow chart of the algorithm for deriving the MxD28C2 product, which contains 8-day area, elevation, and storage results for the 164 reservoirs. The product components are underlined.

### 2.2 MxD28C3 Algorithm

Figure 3 shows the algorithm for generating the MxD28C3 monthly product, which is described in detail in Li et al. (2021). The monthly area values are first estimated based on the composite of the 8-day area classifications, and then converted to monthly elevation and storage results. In addition, monthly evaporation rates are calculated after the Lake Temperature and Evaporation Model (LTEM) (Zhao et al., 2020) using MODIS LST product (MOD21) and meteorological data from Global Land Data Assimilation System (GLDAS). Lastly, monthly evaporative volumetric losses were calculated as the product of evaporation rate and reservoir area values.



**Figure 3.** Flow chart of the algorithm for deriving the MxD28C3 product, which contains monthly area, elevation, storage, evaporation rate, and volumetric evaporation loss results for the 164 reservoirs. The product components are underlined.

### 3. MxD28 Global Water Reservoir Product Suite

#### 3.1 Level 2 8-day Product (MxD28C2)

The MxD28C2 reservoir product contains the 8-day results of the reservoir area, elevation, and storage.

##### 3.1.1 Naming Convention

The file naming convention is as follows:

MxD28C2.AYYYYDDD.061.YYYYDDDDHHMMSS.hdf

where,

MxD = either MOD or MYD. MOD stands for the Terra product, and MYD stands for the Aqua product.

YYYY= Year mapped

DDD = Start day of the year (Julian day) at the 8-day interval (see Table 2 for converting to calendar date)

061 = Collection 6.1

YYYYDDDDHHMMSS = Production time

**Example:** The product file MOD28C2.A2012161.061.2020323115311.hdf contains the Collection 6.1 reservoir results based on MODIS data (onboard of Terra) started on June 9, 2012 (with MODIS data collected during the 8-DAY period of June 9-16, 2012). The file was produced on November 18, 2020 at 11:53:11 UTC.

**Table 2.** Lookup table for converting the start date of the 8-day file from Julian Day to the calendar date

DDD (8-day interval*) (Regular Years)	Corresponding Month and Day (Regular Years)	DDD (8-day interval) (Leap Years)	Corresponding Month and Day (Leap Years)
001, 009, 017, 025	Jan. 1, Jan. 9, Jan 17, Jan 25	001, 009, 017, 025	Jan. 1, Jan. 9, Jan 17, Jan 25
033, 041, 049, 057	Feb. 2, Feb. 10, Feb. 18, Feb. 26	033, 041, 049, 057	Feb. 2, Feb. 10, Feb. 18, Feb. 26
065, 073, 081, 089	Mar. 6, Mar. 14, Mar. 22, Mar. 30	065, 073, 081, 089	Mar. 5, Mar. 13, Mar. 21, Mar. 29
097, 105, 113	Apr. 7, Apr. 15, Apr. 23	097, 105, 113, 121	Apr. 6, Apr. 14, Apr. 22, Apr. 30
121, 129, 137, 145	May 1, May 9, May 17, May 25	129, 137, 145	May 8, May 16, May 24
153, 161, 169, 177	Jun. 2, Jun. 10, Jun. 18, Jun. 26	153, 161, 169, 177	Jun. 1, Jun. 9, Jun. 17, Jun. 25
185, 193, 201, 209	Jul. 4, Jul. 12, Jul. 20, Jul. 28	185, 193, 201, 209	Jul. 3, Jul. 11, Jul. 19, Jul. 27
217, 225, 233, 241	Aug. 5, Aug. 13, Aug. 21, Aug. 29	217, 225, 233, 241	Aug. 4, Aug. 12, Aug. 20, Aug. 28

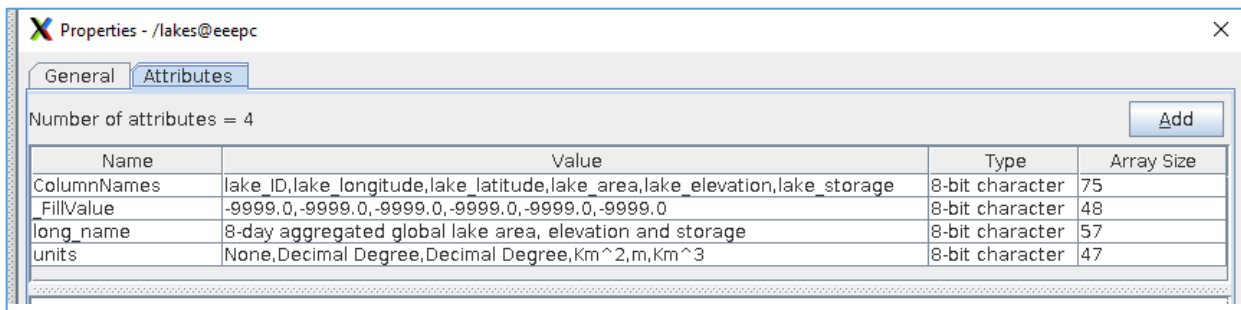
249, 257, 265, 273	Sep. 6, Sep. 14, Sep. 22, Sep. 30	249, 257, 265, 273	Sep. 5, Sep. 13, Sep. 21, Sep. 29
281, 289, 297	Oct. 8, Oct. 16, Oct. 24	281, 289, 297, 305	Oct. 7, Oct. 15, Oct. 23, Oct. 31
305, 313, 321, 329	Nov. 1, Nov. 9, Nov. 17, Nov. 25	313, 321, 329	Nov. 8, Nov. 16, Nov. 24
337, 345, 353, 361 <sup>1</sup>	Dec. 3, Dec. 11, Dec. 19, Dec. 27 <sup>1</sup>	337, 345, 353, 361 <sup>2</sup>	Dec. 2, Dec. 10, Dec. 18, Dec. 26 <sup>2</sup>

<sup>1</sup>File with this start date is only based on the MODIS data from the last 5 days of a normal year;

<sup>2</sup>File with this start date is only based on the MODIS data from the last 6 days of a leap year.

### 3.1.2 Data Layers

The product contains one single layer named ‘lakes’. This layer contains information about the reservoir id, dam location (longitude and latitude), reservoir area, elevation, and storage. Figure 4 shows the general information about the ‘lakes’ layer displayed using HDFView.



lake_ID	lake_longitude	lake_latitude	lake_area	lake_elevation	lake_storage
1	104.322	52.234	32014.30...	455.7564412332...	23579.316088...
2	0.06	6.303	6405.844...	78.99326540675...	90.906088058...
3	32.886	23.967	3691.646...	170.1183753904...	94.941647857...
4	28.76	-16.523	5358.309...	484.9481635509...	177.49038514...
5	101.785	56.284	4601.315...	398.1411787909...	140.54076790...
6	83.348	49.656	4271.331...	390.0682519896...	22.141223418...
7	-62.998	7.764	3941.133...	273.9318833271...	116.78024373...
8	-69.78	54.851	3374.917...	530.1157822669...	11.845852010...
9	-77.451	53.785	2751.172...	174.5277677720...	56.871232083...
10	-40.824	-9.423	2781.815...	391.1519877205...	30.190956203...
11	-99.29	53.16	2624.255...	256.1901215825...	9.3899816340...
12	-75.963	53.729	3083.142...	273.5257875084...	104.40403541...
13	-49.647	-3.833	2761.637...	77.45435942828...	51.020486337...

**Figure 4.** General information about the ‘lakes’ layer displayed using HDFView. Top: sample file imported; Middle: metadata attributes; and Bottom: data information contained in the sample file. The Reservoir ID for the last row (not shown) is 164.

### 3.1.3 Metadata

Detailed description about the metadata can be found in Table 3.

**Table 3.** List of metadata for MxD28C2

Column Name	lake_ID	lake_longitude	lake_latitude	lake_area	lake_elevation	lake_storage
Fill Value	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0
Long name	8-day aggregated global lake area					
Unit	None	Decimal Degree	Decimal Degree	km <sup>2</sup>	m	km <sup>3</sup>

### 3.1.4 Example Codes

Example codes (in Matlab and Python) for reading the MxD28C2 hdf files are provided in Appendix B.

## 3.2 Level 3 Monthly Reservoir Product (MxD28C3)

The MxD28C3 product contains the monthly results of the reservoir area, elevation, storage, evaporation rate, and evaporation volume.

### 3.2.1 Naming Convention

The file naming convention is as follows:

MxD28C3.AYYYYDDD.061.YYYYDDDDHHMMSS.hdf

where,

MxD = either MOD or MYD. MOD stands for the Terra product, and MYD stands for the Aqua product.

YYYY= Year mapped

DDD = Day-of-year (DOY) of the first day of each calendar month (please see Table 4 for more details)

061 = Collection 6.1

YYYYDDDDHHMMSS = Production time

**Example:** The product file MOD28C3.A2012001.061.2020333100640.hdf contains the Collection 6.1 reservoir results based on MODIS data (onboard of Terra) in January 2012. The file was produced on November 28, 2020 at 10:06:40 UTC.

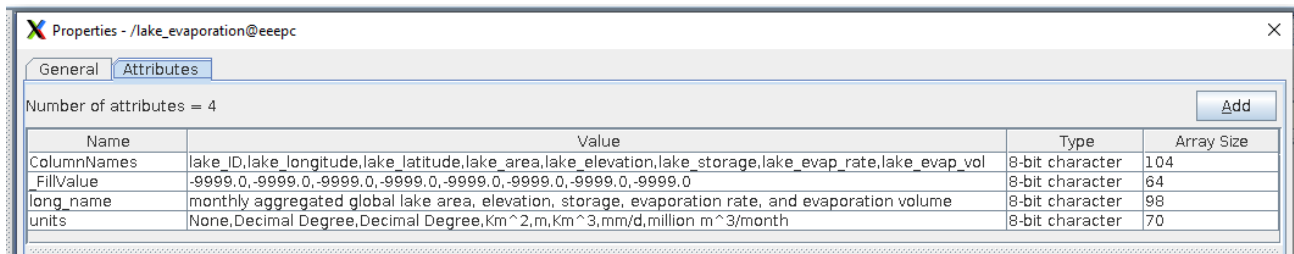


**Table 4.** Day-of-year (DOY) of the first day of each calendar month.

Month	Non-Leap Year Start DOY	Leap Year Start DOY
January	1	1
February	32	32
March	60	61
April	91	92
May	121	122
June	152	153
July	182	183
August	213	214
September	244	245
October	274	275
November	305	306
December	335	336

### 3.2.2 Data Layers

The product contains one single layer named ‘lake\_evaporation’. This layer contains information about the reservoir id, dam location (longitude and latitude), monthly reservoir area, elevation, storage, evaporation rate, and evaporation volume. Figure 5 shows the general information about the ‘lake\_evaporation’ layer displayed using HDFView.



lake_ID	lake_longitude	lake_latitude	lake_area	lake_elevation	lake_storage	lake_evap_rate	lake_evap_vol
1	104.322	52.234	32573.488	458.25394	23659.97	3.5605447	3479.3809
2	0.06	6.303	6398.7603	78.96738	90.740326	4.7594395	913.6354
3	32.886	23.967	3891.6008	171.05533	98.49423	8.277407	966.37085
4	28.76	-16.523	5592.556	487.56955	191.84363	4.7328515	794.06213
5	101.785	56.284	6140.526	408.2501	194.83492	2.4113657	444.2116
6	83.348	49.656	4402.5957	390.67865	24.7885	4.9828753	658.12756
7	-62.998	7.764	4198.67	277.64124	131.877	6.181749	778.6537
8	-69.78	54.851	4471.5547	543.4764	64.26275	1.3763369	184.63097
9	-77.451	53.785	3303.6506	180.6601	75.43632	1.3805424	136.82489
10	-40.824	-9.423	2815.4094	391.3438	30.727795	5.6935124	480.88705
11	-99.29	53.16	2264.4343	255.40887	7.480362	4.389555	298.19577
12	-75.963	53.729	2981.2869	270.94012	96.56375	1.3361756	119.50568
13	-49.647	-3.833	3138.4707	82.4347	65.71276	4.381322	412.5195
14	42.11	47.61	2357.0059	35.377224	13.590457	5.9836955	423.10815
15	127.307	53.771	2593.5598	319.98926	77.3835	2.8863337	224.57637
16	112.477	63.034	2684.0383	259.2802	71.47633	3.088728	248.70793

**Figure 5.** General information about the ‘lake\_evaporation’ layer displayed using HDFView. Top: sample file imported and metadata attributes; and Bottom: data information contained in the sample file. The Reservoir ID for the last row (not shown) is 164.

### 3.2.3 Metadata

A detailed description of the metadata can be found in Table 5.

**Table 5.** List of metadata for MxD28C3

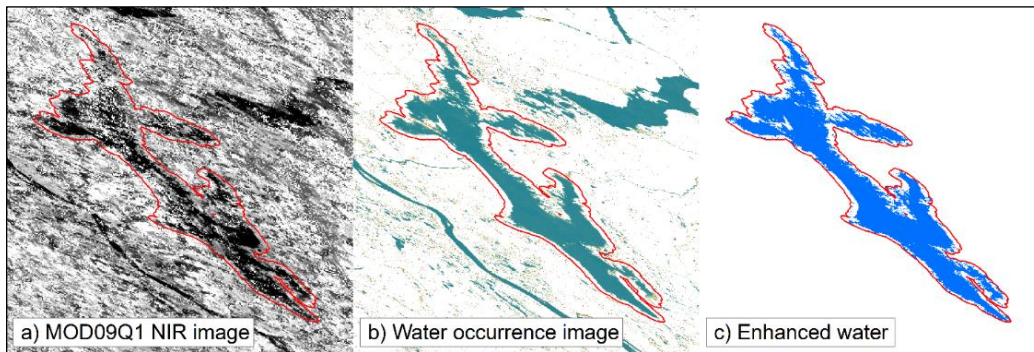
Column Name	lake_ID	lake_longitude	lake_latitude	lake_area	lake_elevation	lake_storage	lake_evap_rate	lake_evap_vol
Fill Value	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0	-9999.0
Long name	monthly aggregated global lake area							
Unit	None	Decimal Degree	Decimal Degree	km <sup>2</sup>	m	km <sup>3</sup>	mm/d	million m <sup>3</sup> /month

### 3.2.4 Example codes

Example codes (in Matlab and Python) for reading the MxD28C3 hdf files are provided in Appendix C.

#### 4. Known Problems

The reliability of the enhancement algorithm depends on the data quality of both water occurrence image and raw water classification. In high latitude regions, the water occurrence image generally shows small surface area dynamics (i.e., the distribution of occurrence values highly skewed to the left). Thus, the pixels with low occurrence values have relatively large uncertainties. In addition, the quality of raw water area classification can be affected by the lake ice coverage. Under such conditions, the enhancement algorithm might generate an incorrect threshold value, typically leading to overestimation of the surface area. This issue will be addressed in a future release of the enhancement algorithm. For the current version, to address this issue in time series analysis, an “outlier removal and gap-filling” script (Appendix B) is recommended to be applied on the 8-day surface area time series.



**Figure 6.** Water classification results for Aug 12, 2012 for Lake Khantayskoye (LAKE\_ID: 17). The enhanced water area shows an overestimated water area.

## 5. Relevant Web and FTP Sites

- MODIS Reservoir Product Overview: General information about the MODIS water reservoir products, with user guide and Algorithm Theoretical Basic Document (ATBD) is provided.  
<https://modis-land.gsfc.nasa.gov/modgwr.html>
- MODIS Reservoir Product Downloading: Websites where MODIS Land products are distributed.  
<https://lpdaac.usgs.gov/> and <https://ladsweb.modaps.eosdis.nasa.gov/>
- Software for visualizing MODIS Reservoir Product: HDFView can be used for viewing the product files and metadata.  
<https://www.hdfgroup.org/downloads/hdfview/>
- Tools for post-processing MODIS Reservoir Product: Scripts from the science team to assist the users to further process the product (e.g., removing outliers from time series).  
<https://dataverse.tdl.org/dataverse/HGao>
- MODIS Reservoir Product Validation:  
(Note: link for publication will be provided later)
- MODIS LDOPE Tools: A collection of programs, written by members of the Land Data Operational Product Evaluation (LDOPE) group, to assist in the analysis and quality assessment of MODIS Land (MODLAND) products.  
<https://ladsweb.modaps.eosdis.nasa.gov/tools-and-services/#ldope>

## 6. References

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, 48(9).

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., ... & Nilsson, C. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9(9), 494-502.

Li, Y., Zhao, G., Shah, D., Zhao, M., Sarkar, S., Devadiga, S., Zhao, B., Zhang, S., and Gao, H., NASA's water reservoir product suite from moderate resolution remote sensing data, *Remote Sensing*, in preparation.

Li, Y., Gao, H., Zhao, G., & Tseng, K. H. (2020). A high-resolution bathymetry dataset for global reservoirs using multi-source satellite imagery and altimetry. *Remote Sensing of Environment*, 244, 111831.

Zhang, S., Gao, H., & Naz, B. S. (2014). Monitoring reservoir storage in South Asia from multisatellite remote sensing. *Water Resources Research*, 50(11), 8927-8943.

Zhao, G., Gao, H., & Cai, X. (2020). Estimating lake temperature profile and evaporation losses by leveraging MODIS LST data. *Remote Sensing of Environment*, 251, 112104.

**Appendix A - List of the 164 Reservoirs and their Attributes**

Lake ID	GRanD_id <sup>1</sup>	Reservoir Name	lon, lat (°)	Country	Continent	A-E Coefficients <sup>2</sup> a, b	Storage capacity (km <sup>3</sup> )	Area capacity (km <sup>2</sup> )	Elevation capacity (m)	Capacity Source <sup>3</sup>
1*	5058	Baikal	104.32, 52.24	Russia	Asia	0.00447, 312.77026	23615.39	32265.61	456.88	GRanD
2	3667	Volta	0.06, 6.3	Ghana	Africa	0.00365, 55.58562	148	8502	86.65	wikipedia
3	4478	Nasser	32.89, 23.97	Egypt	Africa	0.00469, 152.81994	162	6500	183.28	literature
4	4056	Kariba Reservoir	28.76, -16.52	Zambia	Africa	0.01119, 424.98467	180	5400	485.41	wikipedia
5	5055	Bratsk Reservoir	101.78, 56.29	Russia	Asia	0.00657, 367.92163	169.27	5470	403.85	wikipedia
6	4787	Zaysan	83.35, 49.66	Kazakhstan	Asia	0.00465, 370.20585	49.8	5490	395.74	GRanD
7	2294	Guri Reservoir	-63, 7.77	Venezuela	South America	0.0144, 217.16716	135	4250	278.38	wikipedia
8	1995	Caniapiscaw Reservoir	-69.78, 54.85	Canada	North America	0.01218, 488.99841	53.79	4275	541.08	GRanD
9	1394	Robert Bourassa Reservoir	-77.45, 53.79	Canada	North America	0.0111, 143.99061	61.7	2905	176.24	Hydro-Québec
10	2516	Sobradinho Reservoir	-40.82, -9.42	Brazil	South America	0.00571, 375.26816	34.1	3017.9	392.5	GRanD
11	712	Cedar	-99.29, 53.16	Canada	North America	0.00217, 250.49224	9.64	2668.46	256.29	GRanD
12	1396	La Grande 3 Reservoir	-75.96, 53.73	Canada	North America	0.02539, 195.25843	60	2451	257.48	Hydro-Québec
13	2365	Tucuruí Reservoir	-49.65, -3.83	Brazil	South America	0.01322, 40.95573	45.5	2606	75.4	GRanD
14	4375	Tsimlyanskoye Reservoir	42.11, 47.61	Russia	Euro	0.01177, 7.63989	23.86	2702	39.44	literature
15	5834	Zeyskoye Reservoir	127.31, 53.77	Russia	Asia	0.02065, 266.43675	68.4	2420	316.41	wikipedia
16	5180	Vilyuy Reservoir	112.48, 63.03	Russia	Asia	0.02852, 182.74156	35.9	2170	244.62	wikipedia
17	4783	Khantayskoye Reservoir	87.81, 68.16	Russia	Asia	0.00445, 49.76375	23.5	2221.61	59.64	GRanD

18	4505	Cahora Bassa Reservoir	32.7, -15.58	Mozambique	Africa	0.01542, 286.9568	55.8	2739	329.18	wikipedia
19	6	Williston	-122.2, 56.02	Canada	North America	0.0529, 580.99344	39.47	1773	674.79	literature
20	4472	Buhayrat ath Tharthar	43.46, 33.69	Iraq	Asia	0.03955, -19.46261	85.59	2135.54	65	literature
21	5056	Krasnoyarsk Reservoir	92.29, 55.93	Russia	Asia	0.03863, 162.77316	73.3	2000	240.04	wikipedia
22	4623	Kama Reservoir	56.34, 58.12	Russia	Euro	0.00744, 96.07894	12.2	1915	110.32	wikipedia
23	1957	Okeechobee	-81.1, 26.94	United States of America	North America	0.00617, -5.57499	5.2	1536.8	3.9	wikipedia
24	5295	Hungtze	118.73, 33.09	China	Asia	0.00749, 1.45816	13.5	2074.61	17	literature
25	4474	Razazah	43.89, 32.7	Iraq	Asia	0.01457, 11.06852	25.75	1621	34.69	literature
26	2023	Gouin Reservoir	-74.1, 48.36	Canada	North America	0.00068, 402.90611	8.57	1570	403.98	GReND
27	4789	Qapshaghay Bogeni Reservoir	77.1, 43.92	Kazakhstan	Asia	0.00897, 467.10974	28.1	1850	483.71	GReND
28	753	Fort Berthold Reservoir	-101.43, 47.51	United States of America	North America	0.02467, 528.64792	29.38	1477.4	565.1	wikipedia
29	2445	Aperea Reservoir	-56.63, -27.39	Paraguay	South America	0.02242, 48.84199	21	1600	84.71	literature
30	870	Oahe	-100.4, 44.46	United States of America	North America	0.02172, 462.72715	28.35	1429.57	493.78	wikipedia
31	2390	Ilha Solteira Reservoir	-51.38, -20.37	Brazil	South America	0.03237, 290.94542	21.17	1200	329.78	GReND
32	4629	Saratov Reservoir	47.76, 52.05	Russia	Euro	0.02563, -0.27741	12.9	1117.7	28.36	GReND
33	4350	Imandra	32.55, 67.41	Russia	Euro	0.18726, -62.86735	10.8	1062.37	136.07	GReND
34	3640	Kainji Reservoir	4.61, 9.87	Nigeria	Africa	0.03997, 93.99579	15	1071.23	136.81	wikipedia
35	4785	Novosibirskoye	83, 54.84	Russia	Asia	0.01419, 98.78019	8.8	1070	113.97	wikipedia
36	4625	Cheboksary	47.46, 56.14	Russia	Euro	0.02447, 39.29789	13.85	1080.38	65.73	literature
37	4359	Ilmen	31.28, 58.46	Russia	Euro	0.0083, 9.98411	12	1120	19.28	wikipedia

38	4480	Jebel Aulia Reservoir	32.48, 15.24	Sudan	Africa	0.00624, 375.01032	3.5	861.19	380.39	FAO
39	1397	Opinaca Reservoir	-76.58, 52.21	Canada	North America	0.02118, 194.07727	8.5	1040	216.1	wikipedia
40	2392	Furnas	-46.31, -20.67	Brazil	South America	0.0437, 720.07262	22.59	1127.07	769.32	wikipedia
41	2368	Serra da Mesa Reservoir	-48.3, -13.84	Brazil	South America	0.03356, 410.19963	54.4	1784	470.07	wikipedia
42	4624	Votkinsk Reservoir	54.08, 56.8	Russia	Euro	0.03892, 53.1356	9.4	850.82	86.25	wikipedia
43	6201	Argyle Reservoir	128.74, - 16.12	Australia	Oceania	0.02806, 66.43617	10.76	981.21	93.97	wikipedia
44	731	Rainy	-93.36, 48.62	Canada	North America	0.00078, 336.08674	0.69	829.45	336.73	GRanD
45	307	Fort Peck	-106.41, 48	United States of America	North America	0.04376, 643.31691	22.77	969.86	685.76	wikipedia
46	2375	Tres Marias Reservoir	-45.27, -18.21	Brazil	South America	0.03553, 539.11233	21	1040	576.06	wikipedia
47	2012	Pipmuacan Reservoir	-69.77, 49.36	Canada	North America	0.0498, 360.46403	13.9	978	409.16	wikipedia
48	4679	Chardarinskoye	67.96, 41.25	Kazakhstan	Asia	0.01786, 238.24413	5.7	800.66	252.54	wikipedia
49	4626	Nizhnekamsk Reservoir	52.28, 55.7	Russia	Euro	0.0138, 50.37324	13.8	1084	65.34	wikipedia
50	2456	Negro Reservoir	-56.42, -32.83	Uruguay	South America	0.0194, 62.00777	8.8	1070	82.77	wikipedia
51	2343	Chocon Reservoir	-68.76, -39.27	Argentina	South America	0.01519, 365.74893	22	820	378.2	GRanD
52	4442	Ataturk Dam	38.32, 37.49	Turkey	Asia	0.10643, 454.25042	48.7	817	541.2	GRanD
53	2513	Itaparica Reservoir	-38.31, -9.14	Brazil	South America	0.03337, 279.33376	10.7	781.21	305.4	wikipedia
54	4464	Assad	38.55, 35.86	Syria	Asia	0.05942, 266.62629	11.7	610	302.87	wikipedia
55	3650	Lagdo Reservoir	13.69, 9.06	Cameroon	Africa	0.0374, 190.15542	7.7	691.12	216	FAO
56	1269	Toledo Bend Reservoir	-93.57, 31.18	United States of America	North America	0.02039, 39.45546	5.52	636.18	52.43	wikipedia
57	6922	Eastmain Reservoir	-75.89, 52.19	Canada	North America	0.06785, 245.91598	6.94	602.9	286.82	literature



58	2009	Outardes 4 Reservoir	-68.91, 49.71	Canada	North America	0.19049, 239.61011	24.5	640	361.53	Hydro-Québec
59	4349	Kovdozero	31.76, 68.6	Russia	Euro	0.00193, 78.17686	3.7	745	79.62	GRanD
60	2380	Sao Simao Reservoir	-50.5, -19.02	Brazil	South America	0.0523, 369.16877	12.5	703	405.94	wikipedia
61	610	Mead	-114.73, 36.02	United States of America	North America	0.13619, 288.76038	34.07	659.3	374.6	USBR
62	5087	Yamdrok	90.38, 29.1	China	Asia	0.01275, 4435.35521	14.6	638	4443.49	literature
63	1391	Angostura Reservoir	-92.78, 16.4	Mexico	North America	0.08079, 478.95889	18.2	640	530.67	wikipedia
64	4991	Srisaillam Reservoir	78.9, 16.09	India	Asia	0.03079, 253.3044	8.29	534.05	269.75	CWC
65	2455	Grande Reservoir	-57.94, -31.27	Argentina	South America	0.03068, 16.88963	5	592.83	35.08	wikipedia
66	4843	Gandhisagar Reservoir	75.55, 24.7	India	Asia	0.03366, 379.03449	6.83	619.89	399.9	CWC
67	2397	Promissao Reservoir	-49.78, -21.3	Brazil	South America	0.08038, 342.73167	7.41	513.39	384	GRanD
68	282	Arrow	-117.78, 49.34	Canada	North America	0.17477, 351.0668	10.3	504.82	439.3	USACE
69	2382	Agua Vermelha Reservoir	-50.35, -19.87	Brazil	South America	0.05626, 351.61681	11.03	563.15	383.3	wikipedia
70	4898	Hirakud Reservoir	83.85, 21.52	India	Asia	0.02204, 177.26302	5.38	669.62	192.02	CWC
71	3041	Kossour Reservoir	-5.47, 7.03	Ivory Coast	Africa	0.03423, 169.77945	27.68	1058.2	206	GRanD
72	4784	Kureiskaya	88.29, 66.95	Russia	Asia	0.04971, 67.89284	9.96	558	95.63	literature
73	3071	Storsjon	14.47, 63.3	Sweden	Euro	0.00422, 291.0872	8.02	484.6	293.13	GRanD
74	316	Flathead Lake	-114.23, 47.68	United States of America	North America	0.13239, 816.09051	23.2	510	883.61	wikipedia
75	2004	Kempt	-70.53, 50.66	Canada	North America	0.03312, 478.60112	2.22	470.44	494.18	GRanD
76	6700	Kolyma dam	150.23, 62.05	Russia	Asia	0.13658, 390.9085	15.08	454.6	453	wikipedia

77	4501	Mtera Reservoir	35.98, -7.14	United Republic of Tanzania	Africa	0.02183, 688.04662	3.2	478.83	698.5	literature
78	4686	Kayrakkumskoye	69.82, 40.28	Tajikistan	Asia	0.02143, 335.23897	4.2	513	346.23	wikipedia
79	250	Kinbasket	-118.57, 52.08	Canada	North America	0.31717, 622.76738	24.76	430	759.15	wikipedia
80	4634	Mingechaurskoye	47.03, 40.8	Azerbaijan	Asia	0.07215, 42.01887	15.73	567.97	83	wikipedia
81	2431	Lago del Río Yguazú	-54.97, -25.37	Paraguay	South America	0.04517, 203.13232	8.47	620	231.14	wikipedia
82	4858	Govind Ballabah Pant	83, 24.2	India	Asia	0.06208, 241.75327	5.65	426.36	268.22	CWC
83	4422	Keban Baraji	38.76, 38.81	Turkey	Asia	0.11302, 772.50564	30.6	675	848.79	wikipedia
84	2340	Los Barreales	-68.69, -38.58	Argentina	South America	0.30759, 290.07305	27.7	413	417.11	literature
85	4859	Bansagar Lake	81.29, 24.19	India	Asia	0.05088, 317.64432	5.17	471.6	341.64	CWC
86	1275	Sam Rayburn Reservoir	-94.11, 31.07	United States of America	North America	0.0355, 35.65711	3.55	455.64	50.11	TWDB
87	2414	Barra Bonita	-49.23, -23.21	Brazil	South America	0.00228, 565.24837	7.01	542	566.48	GRanD
88	4739	Ukal	73.6, 21.26	India	Asia	0.04229, 83.59772	6.62	509.85	105.16	CWC
89	479	Utah Lake	-111.89, 40.36	United States of America	North America	0.02307, 1359.51211	1.07	380	1368.28	wikipedia
90	305	Pend Oreille Lake	-117, 48.18	United States of America	North America	0.22845, 541.65792	54.2	381.47	628.8	wikipedia
91	4994	Tungabhadra	76.33, 15.27	India	Asia	0.04122, 483.33699	3.28	349.42	497.74	CWC
92	4461	Mosul Dam Lake	42.83, 36.63	Iraq	Asia	0.16032, 273.38375	11.1	353.16	330	wikipedia
93	4470	Habbaniyah	42.35, 34.21	Iraq	Asia	0.07125, 114.61642	8.2	418.4	144.43	literature
94	4946	Sriramsagar Reservoir	78.34, 18.97	India	Asia	0.04005, 319.94975	2.3	314.38	332.54	CWC
95	2376	Lago das Brisas	-49.1, -18.41	Brazil	South America	0.08818, 471.03368	17	559.6	520.38	wikipedia

96	2356	Meelpaeg	-56.78, 48.17	Canada	North America	0.0041, 269.35893	2.16	314.9	270.65	GRanD
97	4260	Hendrik Verwoerd	25.5, -30.62	South Africa	Africa	0.06907, 1236.10289	5.34	374	1261.93	wikipedia
98	1387	Malpaso	-93.6, 17.18	Mexico	North America	0.30032, 89.06386	9.17	309.45	182	literature
99	1379	Inhernillo	-101.89, 18.27	Mexico	North America	0.14118, 116.65544	12	400	173.13	wikipedia
100	4184	Vaaldam	28.12, -26.88	South Africa	Africa	0.0358, 1472.81742	2.61	320	1484.27	wikipedia
101	5062	Longyangxia	100.92, 36.12	China	Asia	0.18321, 2518.97907	24.7	383	2589.15	wikipedia
102	3727	Hoytiainen	29.48, 62.83	Finland	Euro	0.0064, 86.17122	2.39	293	88.05	GRanD
103	1423	Baskatong	-75.98, 46.72	Canada	North America	0.05663, 207.28526	2.63	280	223.14	GRanD
104	5803	Tri An Lake	107.04, 11.11	Vietnam	Asia	0.07216, 39.48203	2.76	323	62.79	wikipedia
105	2007	Peribonka	-71.25, 49.9	Canada	North America	0.10611, 411.5385	5.18	270.72	440.26	GRanD
106	4942	Jayakwadi	75.37, 19.49	India	Asia	0.03201, 451.67121	2.17	382.39	463.91	CWC
107	3638	Shiroro	6.84, 9.97	Nigeria	Africa	0.08602, 350.89662	7	312	377.73	FAO
108	4379	Tshchikskoye	39.12, 44.99	Russia	Euro	0.06161, 16.03972	3.05	286.28	33.68	FAO
109	710	Tobin	-103.4, 53.66	Canada	North America	0.00897, 311.22766	2.2	263.86	313.59	GRanD
110	5796	Noi	105.43, 15.21	Thailand	Asia	0.05709, 129.50217	1.97	288	145.94	wikipedia
111	4483	Roseires Reservoir	34.39, 11.8	Sudan	Africa	0.02506, 475.84407	7.4	450	487.12	wikipedia
112	4675	Toktogul'skoye	72.65, 41.68	Kyrgyzstan	Asia	0.55471, 743.53409	19.5	284.3	901.24	wikipedia
113	6698	Gordon	145.98, - 42.73	Australia	Oceania	0.37007, 208.53588	12.4	278	311.42	wikipedia
114	4964	Ujani	75.12, 18.07	India	Asia	0.05453, 482.16622	1.52	268.91	496.83	CWC
115	2312	Hondo	-64.89, -27.52	Argentina	South America	0.02922, 266.72004	1.74	330	276.36	WLDB

116	4362	Ivankovo Reservoir	37.12, 56.73	Russia	Euro	0.01794, 119.50914	1.17	220.57	123.47	GRanD
117	4702	Tarbela	72.69, 34.09	Pakistan	Asia	0.52839, 351.45663	13.69	250	483.55	wikipedia
118	4985	Nagarjuna	79.31, 16.57	India	Asia	0.29044, 100.77784	6.84	272.18	179.83	wikipedia
119	3070	Kallsjon	13.34, 63.43	Sweden	Euro	0.02782, 387.52135	6.14	189.74	392.8	GRanD
120	4431	Karakaya	39.14, 38.23	Turkey	Asia	0.22073, 631.76449	9.5	298	697.54	wikipedia
121	4792	Beas	75.95, 31.97	India	Asia	0.20473, 371.49329	6.16	254.85	423.67	CWC
122	4047	Tshangalele	27.24, -10.75	Democratic Republic of the Congo	Africa	0.03102, 1119.03312	1.06	225.65	1126.03	GRanD
123	4485	Finchaa	37.36, 9.56	Ethiopia	Africa	0.01891, 2216.55235	0.65	196.13	2220.26	FAO
124	4989	Almatti	75.89, 16.33	India	Asia	0.05275, 504.12335	3.11	293.42	519.6	CWC
125	4707	Mangla	73.64, 33.15	Pakistan	Asia	0.20109, 320.1312	9.12	251	370.6	wikipedia
126	4836	Rana Pratap	75.58, 24.92	India	Asia	0.1391, 324.74	1.44	197.66	352.81	CWC
127	3014	Bagre	-0.55, 11.47	Burkina Faso	Africa	0.05719, 223.53693	1.7	255	238.12	literature
128	1991	Junin	-76.19, -10.98	Peru	South America	0.02312, 4079.83703	1.08	206.71	4084.62	WLDB
129	4881	Bargi Dam Reservoir	79.93, 22.95	India	Asia	0.08518, 401.51078	3.18	236.24	422.76	CWC
130	6686	Great Lake	146.73, - 41.98	Australia	Oceania	0.40346, 969.53157	3.36	176	1040.54	GRanD
131	6800	Hawea	169.25, - 44.61	New Zealand	Oceania	0.14631, 323.54085	2.18	150	345.49	GRanD
132	3676	Albufeira da Quiminha	13.79, -8.96	Angola	Africa	0.13121, 34.99206	1.56	129.05	51.93	GRanD
133	6629	Eucumbene	148.62, - 36.13	Australia	Oceania	0.46484, 1097.64507	4.8	145.42	1165.24	wikipedia
134	1320	Falcon Reservoir	-99.17, 26.56	United States of America	North America	0.06972, 71.73912	3.88	311.84	93.48	TWDB

135	597	Lake Powell	-111.49, 36.94	United States of America	North America	0.1406, 1047.2	30	609.38	1127.76	wikipedia
136	4463	Dukan	44.96, 35.96	Iraq	Asia	0.18893, 462.6788	6.97	270	513.69	wikipedia
137	1230	Cedar Creek Reservoir	-96.07, 32.18	United States of America	North America	0.09423, 85.91971	0.8	133.03	98.15	TWDB
138	4041	Lake Maga	15.05, 10.83	Cameroon	Africa	0.01933, 309.62551	0.68	148.72	312.5	literature
139	5157	Pasak Chonlasit	101.08, 14.85	Thailand	Asia	0.05295, 33.58769	0.79	158.87	42	literature
140	6594	Fairbairn	148.06, - 23.65	Australia	Oceania	0.13, 186.48395	2.29	179.43	209.81	wikipedia
141	6628	Hume	147.03, - 36.11	Australia	Oceania	0.15399, 161.81633	3.04	201.9	192	wikipedia
142	4500	Kikuletwa	37.47, -3.82	United Republic of Tanzania	Africa	0.1, 677.01366	0.6	126.33	689.65	wikipedia
143	4958	Nizam sagar	77.93, 18.2	India	Asia	0.0893, 419.95709	0.5	92.75	428.24	CWC
144	6606	Victoria	141.28, - 34.04	Australia	Oceania	0.16558, 7.52685	0.68	122	27.73	GRand
145	1869	Grenada Lake	-89.77, 33.82	United States of America	North America	0.12614, 49.34905	1.54	128.29	65.53	Lakes Online
146	138	Canyon	-121.09, 40.18	United States of America	North America	0.68749, 1300.93547	1.61	108.39	1373.12	wikipedia
147	4638	Aras Dam Lake	45.4, 39.09	Azerbaijan	Asia	0.11845, 762.76554	1.35	145	779.94	wikipedia
148	4481	Khashm el-Girba	35.9, 14.93	Sudan	Africa	0.09342, 463.08227	1.3	125	474.76	wikipedia
149	370	Lake Cascade	-116.05, 44.52	United States of America	North America	0.16232, 1455.02068	0.85	101.98	1471.57	wikipedia
150	3695	Seitevare	18.57, 66.97	Sweden	Euro	0.62918, 419.1852	1.68	81	470.15	GRand
151	4484	Yardi	40.54, 10.23	Ethiopia	Africa	0.33044, 533.59442	2.32	104.87	568.25	GRand
152	119	Clear Lake Reservoir	-121.08, 41.93	United States of America	North America	0.19968, 1345.80215	0.65	100.36	1365.84	wikipedia
153	5196	Guanting Shuiku	115.6, 40.23	China	Asia	0.10764, 465.09336	4.16	130	479.09	GRand

154	2953	Barrage Al Massira	-7.64, 32.47	Morocco	Africa	0.33916, 241.40761	2.76	80	268.54	wikipedia
155	1319	Venustiano Carranza	-100.62, 27.51	Mexico	North America	0.09456, 252.29236	1.31	150.56	266.53	literature
156	4471	Lake Hamrin	44.97, 34.12	Iraq	Asia	0.11963, 80.22516	4.61	228	107.5	literature
157	4826	Matatila	78.37, 25.1	India	Asia	0.10028, 297.22136	0.71	112.07	308.46	CWC
158	1263	Twin Buttes	-100.52, 31.37	United States of America	North America	0.49517, 576.78181	0.23	29.47	591.37	TWDB
159	4997	Somasila	79.3, 14.49	India	Asia	0.17144, 74.32045	1.99	153.17	100.58	CWC
160	5183	Hongshan Reservoir	119.7, 42.75	China	Asia	0.23268, 422.07692	2.56	66.9	437.64	GRanD
161	6583	Lake Ross	146.74, - 19.41	Australia	Oceania	0.11178, 32.60497	0.8	82	41.77	wikipedia
162	4978	Yeleru Reservoir	82.08, 17.3	India	Asia	0.58856, 57.51076	0.51	49.36	86.56	CWC
163	4696	South Surkhan Reservoir	67.63, 37.83	Uzbekistan	Asia	0.33795, 397.79868	0.8	40.26	411.41	GRanD
164	5287	Zhaopingtai Reservoir	112.77, 33.73	China	Asia	0.35804, 157.62551	0.71	46.5	174.27	GRanD

\* The 164 reservoirs include 13 regulated natural lakes, whose IDs are 1, 6, 20, 23, 33, 37, 44, 62, 73, 102, 131, 150, and 151.

<sup>1</sup> GRanD: Global Reservoir and Dam Database (Lehner et al., 2011). All of the geographical location information is adopted from GRanD.

<sup>2</sup> a and b are the coefficients used in the A-E relationship equation:  $h=a*A+b$ , where h and A are elevation (m) and area (km<sup>2</sup>), respectively.

<sup>3</sup> List of full names: FAO- Food and Agriculture Organization; USBR- United States Bureau of Reclamation; CWC- Central Water Commission of India; USACE- United States Army Corps of Engineers; TWDB- Texas Water Development Board; WLDB- World Lake Database.

## **Appendix B- Example codes (in MATLAB and Python) for reading MxD28C2 hdf files**

### **1) MATLAB code for reading the MxD28C2 hdf file**

```
%%% To get information about the file %%%  
  
a=hdfinfo('MYD28C2.A2012225.061.2020323120640.hdf');  
  
%%% Read the data %%%  
  
b=a.Vdata;  
  
x=hdfread(b,'Fields',{'lake_ID','lake_longitude','lake_latitude','lake_area','lake_elevation','lake_storage'});  
  
lake_id= x{1,1};  
longitude= x{2,1};  
latitude=x{3,1};  
area=x{4,1};  
elevation=x{5,1};  
storage=x{6,1};
```

### **2) Short version of the MATLAB code for reading the MxD28C2 hdf file**

```
%% Other way to read the data  
  
a=hdfinfo('MYD28C2.A2012225.061.2020323120640.hdf');  
  
%%% go to a.Vdata and find the name of the layer-> here it is 'lakes'  
  
%%% just use this layer name to read the data  
  
k=hdfread('C:\Users\User\Desktop\MYD28C2.A2012225.061.2020323120640.hdf','lakes');  
  
%%% The values in variable 'k' are in same order as a.Vdata.Field  
  
%%% Here it is lake_ID, lake_longitude, lake_latitude, lake_area, lake_elevation, lake_storage, respectively.
```

### 3) Python code for reading the MxD28C2 data from the hdf file

```
#####  
from pyhdf.HDF import HDF  
import pyhdf.VS  
  
##input the HDF filename and open it  
filename = "MOD28C2.A2012161.061.2020323115311.hdf"  
f=HDF(filename)  
  
##open the data table  
vs=f.vstart()  
vd=vs.attach('lakes')  
  
##get the filed names  
columns=vd._fields  
print (columns)  
  
##read the data table content  
for i in vd[:]:  
    print (i)  
  
##close the data table  
vd.detach()  
vs.end()  
f.close()  
#####
```



## **Appendix C- Example codes (in MATLAB and Python) for reading MxD28C3 hdf files**

### **1) MATLAB code for reading the MxD28C3 hdf file**

```
%%% To get information about the file %%%  
  
a=hdfinfo('MOD28C3.A2012001.hdf');  
  
%%% Read the data %%%  
  
b=a.Vdata;  
  
x=hdfread  
(b,'Fields',{'lake_ID','lake_longitude','lake_latitude','lake_area','lake_elevation','lake_storage','lake_evap_rate','lake_evap_vol'});  
  
lake_id= x{1,1}';  
longitude= x{2,1}';  
latitude=x{3,1}';  
area=x{4,1}';  
elevation=x{5,1}';  
storage=x{6,1}';  
evaporation_rate=x{7,1}';  
evaporation_volume=x{8,1}';
```

### **2) Short version of the MATLAB code for reading the MxD28C3 hdf file**

```
a=hdfinfo('MOD28C3.A2012001.hdf');  
  
%%% go to a.Vdata and find the name of the layer-> here it is 'lake_evaporation'  
  
%%% just use this layer name to read the data  
  
k=hdfread('MOD28C3.A2012001.hdf','lake_evaporation');  
  
%%% The values in variable 'k' are in same order as a.Vdata.Fields  
  
%%% Here it is Lake_ID, Lake_longitude, Lake_latitude, Lake_area, Lake_elevation, Lake_storage, Lake_evaporation_rate,  
and Lake_evaporation_volume, respectively.
```

### 3) Python code for reading the MxD28C3 data from the hdf file

```
from pyhdf.HDF import HDF
import pyhdf.VS

##input the HDF filename and open it
filename = "MOD28C3.A2012001.hdf"
f=HDF(filename)

## initialize the data table
vs=f.vstart()
##return data information
vdata_info=vs.vdatainfo()
##open the data table
vd=vs.attach('lake_evaporation')
##get the filed names
columns=vd._fields
print (columns)
##read the data table content
for i in vd[:]:
    print (i)

##close the data table
vd.detach()
vs.end()
f.close()
```

## **Appendix D – Outlier removal and gap filling script**

To use this attached script, copy the code below to a file (e.g., process.py). Then run the script using python (with prerequisite packages installed) by typing: python process.py input.csv. The input.csv is a csv file contains the time series of lake\_area values prepared by the user. The first column is date (year\_doy, e.g., 2012009) and the second column is the lake\_area value. Output file (input\_new.csv) contains a new column with the lake\_area\_new values.

```
import numpy as np
import pandas as pd
import glob
import sys, os
from datetime import datetime

def remove_bias(values, dates, wz):

    weight = np.arange(1,wz,1)[int(wz/2):]
    weight = np.concatenate((weight, np.ones(len(values)-wz+1)*wz, np.flip(weight, 0)))/wz

    nol = 2
    limit = 50
    while nol > 0 and limit > 0:
        wt_ma = np.convolve(values, np.ones((wz,))/wz, mode='same')

        bias = values - wt_ma/weight
        b_avg = np.average(bias)
        b_sd = np.std(bias)

        outlier = [0 if (x >= b_avg+3*b_sd or x <= b_avg-3*b_sd) else 1 for x in bias]
        inreduce = nol - (len(outlier) - np.sum(outlier))
        nol = len(outlier) - np.sum(outlier)
        limit = limit - 1

        n_mth = [x for x,y in zip(dates, outlier) if y==1]
        n_enh = [x for x,y in zip(values, outlier) if y==1]
        if len(n_mth) >= 5:
            values = np.interp(dates, n_mth, n_enh)
        else:
            return dates, values
        if inreduce == 0 and nol <=2:
            break
    return n_mth, n_enh

def main(argv):

    fname = sys.argv[1]

    print('Processing: ', fname)
```

```
if not os.path.exists(fname):
    print('Error: cannot find file!')
    sys.exit(0)

df = pd.read_csv(fname, sep=',')

df['date0'] = pd.to_datetime(df['year_doy'], format='%Y%j')
df['date'] = (df['date0'] - pd.to_datetime('2000-01-01'))/np.timedelta64(1, 'D')

##### interpolate the water area #####
df_valid = df[(df['lake_area'] > 0)]

N = 7 # moving window
if len(df_valid.index) > N:

    ##### remove outliers #####
    water_enh_int = df_valid['lake_area'].values
    dates = df_valid['date'].values
    n_mth, n_enh = remove_bias(water_enh_int, dates, N)

    df['lake_area_new'] = np.interp(df['date'], n_mth, n_enh)

    nname = fname.replace('.csv', '_new.csv')
    df[['year_doy', 'lake_area', 'lake_area_new']].to_csv(nname, sep=',', index=False)

if __name__ == "__main__":
    main(sys.argv[1:])
```