Supplement of

Satellite observations reveal 13 years of reservoir filling strategies, operating rules, and hydrological alterations in the Upper Mekong River basin

Dung Trung Vu et al.

Correspondence to: Stefano Galelli (stefano_galelli@sutd.edu.sg)

The copyright of individual parts of the supplement might differ from the article licence.
Text S1. Commonalities and differences between our study and the Mekong Dam Monitor

Both our study and the Mekong Dam Monitor (MDM) are based on the idea of extracting the water extent of the reservoirs from satellite images and then converting it into water level and storage by using the information from a Digital Elevation Model (DEM). However, there are a few key differences. First, we use an image improvement algorithm, which is important and necessary because it enables us to extract the information on reservoir storage from Landsat images for a long period (2008–2020). Meanwhile, to avoid the cloud contamination in satellite images, MDM looks to other remote sensing products, such as the Sentinel-SAR (Synthetic Aperture Radar), which can “pierce” through clouds. However, Sentinels were launched recently (in April 2014), so the information before that time (including the construction and filling periods of five reservoirs on the mainstream of the Lancang) cannot be revealed. Second, with the water extent estimation provided by our algorithm, we directly infer water level and storage through the elevation-area-storage curves estimated from the DEM. Meanwhile, MDM calculates the average elevation at the reservoir shoreline, and then converts it into storage. This way may not work well for all water surface images. Finally, to strengthen our results, we make use of water level from Altimetry data (where available) to validate the results obtained by processing the Landsat images.
Table S1. Design specifications of the hydropower dams on the mainstream of the Lancang River. Retrieved from Do et al. (2020).

| Name of Dam | Year of Commission | Dam Height (m) | WL (m a.s.l.) | Max Dead WL (m a.s.l.) | WL (m a.s.l.) | WSA (km²) | Storage (MCM) | Full Storage (MCM) | Hydropower Capacity (MW) |
|-------------|-------------------|---------------|--------------|------------------------|--------------|-----------|--------------|---------------------|------------------------|
| Jinghong    | 2009              | 108           | 602          | 595                   | 510          | 810       | 1119         | 1750                |                        |
| Nuozhadu    | 2014              | 262           | 812          | 756                   | 320          | 10414     | 21749        | 5850                |                        |
| Dachaoshan  | 2003              | 115           | 899          | 887                   | 826          | 465       | 740          | 1350                |                        |
| Manwan      | 1992              | 132           | 994          | 982                   | 415          | 630       | 887          | 1670                |                        |
| Xiaowan     | 2010              | 292           | 1236         | 1162                  | 194          | 4750      | 14645        | 4200                |                        |
| Gongguoqiao | 2012              | 105           | 1319         | 1311                  | 343          | 196       | 316          | 900                 |                        |
| Miaowei     | 2016              | 140           | 1408         | 1373                  | 171          | 359       | 660          | 1400                |                        |
| Dahuaqiao   | 2018              | 106           | 1477         | 1466                  | 148          | 252       | 293          | 920                 |                        |
| Huangdeng   | 2017              | 203           | 1619         | 1604                  | 199          | 1031      | 1418         | 1900                |                        |
| Tuoba       | 2023              | 158           | 1735         | 1725                  | 177          | 735       | 1039         | 1400                |                        |
| Lidi        | 2019              | 74            | 1818         | 1813                  | 4            | 57        | 71           | 420                 |                        |
| Wunonglong  | 2018              | 138           | 1906         | 1894                  | 163          | 236       | 272          | 990                 |                        |

WL: Water level  
WSA: Water surface area
### Table S2. Specifications of Landsat, MODIS and Sentinel images.

| Satellite | Landsat (NASA and USGS) | MODIS (NASA) | Sentinel (ESA) |
|-----------|--------------------------|--------------|----------------|
|           | 1-3  | 4-5 | 7  | 8   | 1 | 2 | 3 |
| First Launch | 1972 | 1982 | 1999 | 2013 | 1999 | 2014 | 2015 | 2016 |
| Instrument | MSS   | MSS, TM | ETM+ | OLI, TIRS | MODIS | SAR | MSI | OLCI |
| Best Resolution | 60 m | 30 m | 30 m | 30 m | 250 m | 5 m | 10 m | 300 m |
| Frequency (Day) | 16 | 16 | 16 | 16 | 1 | 12 | 10 | 27 |
| Cloud Cover | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes |

- **MODIS**: Moderate Resolution Imaging Spectroradiometer
- **USGS**: United States Geological Survey
- **ESA**: European Space Agency
- **MSS**: Multi Spectral Scanner
- **TM**: Thematic Mapper
- **ETM+**: Enhanced Thematic Mapper Plus
- **OLI**: Operational Land Imager
- **TIRS**: Thermal Infrared Sensor
- **SAR**: Synthetic Aperture Rada
- **MSI**: Multi-Spectral Instrument
- **OLCI**: Ocean and Land Colour Instrument
Table S3. Specifications of satellite altimeters.

| Satellite        | Type | Organization          | Operation Time | Repeat Period (day) |
|------------------|------|-----------------------|----------------|---------------------|
| Topex/Poseidon   | Radar| NASA and CNES         | 1992-2002      | 10                  |
| Jason 1          | Radar| NASA and CNES         | 2002-2008      | 10                  |
| Jason 2          | Radar| NASA and CNES         | 2008-2016      | 10                  |
| Jason 3          | Radar| NASA and CNES         | 2016-current   | 10                  |
| ERS 1            | Radar| ESA                   | 1992-1996      | 35                  |
| ERS 2            | Radar| ESA                   | 1996-2003      | 35                  |
| Envisat          | Radar| ESA                   | 2002-2010      | 35                  |
| SARAL            | Radar| ISRO and CNES         | 2013-2016      | 35                  |
| Sentinel 3A      | Radar| ESA                   | 2016-current   | 27                  |
| Sentinel 3B      | Radar| ESA                   | 2018-current   | 27                  |
| ICESat 1         | Laser| NASA                  | 2003-2009      | 91                  |
| ICESat 2         | Laser| NASA                  | 2018-current   | 91                  |

CNES    National Centre for Space Studies
ESA     European Space Agency
ISRO    Indian Space Research Organization
ERS     European Remote Sensing
SARAL   Satellite with ARgos and ALtika
ICESat  Ice, Cloud, and land Elevation Satellite
| Water Level (m) | Nuozhadu Storage [1] (MCM) | Nuozhadu Storage [2] (MCM) | Difference (%) | Xiaowan Storage [1] (MCM) | Xiaowan Storage [2] (MCM) | Difference (%) |
|----------------|-----------------------------|-----------------------------|----------------|-----------------------------|-----------------------------|----------------|
| 766            | 10501                       | 10678                       | 1.67           | 1162                       | 4077                        | 1.74           |
| 768            | 10859                       | 11042                       | 1.65           | 1164                       | 4223                        | 1.74           |
| 770            | 11227                       | 11414                       | 1.64           | 1166                       | 4375                        | 1.73           |
| 772            | 11605                       | 11797                       | 1.63           | 1168                       | 4531                        | 1.74           |
| 774            | 11992                       | 12189                       | 1.62           | 1170                       | 4693                        | 1.74           |
| 776            | 12390                       | 12592                       | 1.61           | 1172                       | 4862                        | 1.74           |
| 778            | 12798                       | 13005                       | 1.59           | 1174                       | 5036                        | 1.74           |
| 780            | 13216                       | 13428                       | 1.58           | 1176                       | 5217                        | 1.74           |
| 782            | 13645                       | 13862                       | 1.57           | 1178                       | 5403                        | 1.73           |
| 784            | 14084                       | 14307                       | 1.56           | 1180                       | 5595                        | 1.71           |
| 786            | 14534                       | 14763                       | 1.55           | 1182                       | 5792                        | 1.70           |
| 788            | 14995                       | 15230                       | 1.54           | 1184                       | 5994                        | 1.68           |
| 790            | 15468                       | 15709                       | 1.53           | 1186                       | 6201                        | 1.67           |
| 792            | 15953                       | 16199                       | 1.52           | 1188                       | 6413                        | 1.65           |
| 794            | 16450                       | 16702                       | 1.51           | 1190                       | 6630                        | 1.64           |
| 796            | 16958                       | 17217                       | 1.50           | 1192                       | 6853                        | 1.62           |
| 798            | 17479                       | 17743                       | 1.49           | 1194                       | 7081                        | 1.61           |
| 800            | 18012                       | 18283                       | 1.48           | 1196                       | 7316                        | 1.60           |
| 802            | 18557                       | 18834                       | 1.47           | 1198                       | 7555                        | 1.59           |
| 804            | 19115                       | 19399                       | 1.46           | 1200                       | 7801                        | 1.57           |
| 806            | 19686                       | 19975                       | 1.45           | 1202                       | 8052                        | 1.56           |
| 808            | 20269                       | 20565                       | 1.44           | 1204                       | 8308                        | 1.54           |
| 810            | 20865                       | 21167                       | 1.43           | 1206                       | 8570                        | 1.53           |
| 812            | 21473                       | 21781                       | 1.42           | 1208                       | 8838                        | 1.51           |
Table S5. Spectral indices for water surface extraction.

| Index   | Formula                  | Recommended Threshold Values                                                                 |
|---------|--------------------------|---------------------------------------------------------------------------------------------|
| NDVI    | (Red-Green)/(Red+Green) | 0 (Zhai et al., 2015) and 0.1 (Gao et al., 2012)                                             |
| NDWI    | (Green-NIR)/(Green+NIR) | 0 (Zhai et al., 2015), (Bonnema and Hossain, 2017)                                          |
| MNDWI   | (Green-MIR)/(Green+MIR) | 0 and 0.1 (Duan and Bastiaanssen, 2013)                                                     |

NDVI       Normalized Difference Vegetation Index  
NDWI       Normalized Difference Water Index  
MNDWI      Modified Normalized Difference Water Index  
NIR        Near Infrared  
MIR        Middle Infrared
Table S6. Performance of the water surface area estimation algorithm for the reservoirs on the Lancang River.

| Reservoir | Number of Available Images | Percentage of Usable Images Before Improvement | After Improvement |
|-----------|-----------------------------|-----------------------------------------------|-------------------|
| **Dry season (Dec-May)** | | | |
| Jinghong | 175 | 24% | 89% |
| Nuozhadu | 187 | 27% | 89% |
| Dachaoshan | 187 | 26% | 89% |
| Manwan | 187 | 25% | 85% |
| Xiaowan | 187 | 27% | 88% |
| Gongguoqiao | 173 | 34% | 75% |
| Miaowei | 173 | 36% | 84% |
| Dahuajiao | 173 | 36% | 82% |
| Huangdeng | 164 | 34% | 85% |
| Wunonglong | 164 | 34% | 73% |
| **Total** | **1770** | **30%** | **84%** |
| **Wet season (Jun-Nov)** | | | |
| Jinghong | 122 | 20% | 80% |
| Nuozhadu | 127 | 13% | 69% |
| Dachaoshan | 130 | 16% | 76% |
| Manwan | 131 | 18% | 77% |
| Xiaowan | 130 | 16% | 88% |
| Gongguoqiao | 118 | 23% | 69% |
| Miaowei | 118 | 27% | 90% |
| Dahuajiao | 118 | 28% | 81% |
| Huangdeng | 120 | 27% | 78% |
| Wunonglong | 120 | 20% | 81% |
| **Total** | **1234** | **21%** | **79%** |
| **Total** | | | |
| Jinghong | 297 | 22% | 85% |
| Nuozhadu | 314 | 21% | 81% |
| Dachaoshan | 317 | 22% | 84% |
| Manwan | 318 | 22% | 82% |
| Xiaowan | 317 | 23% | 88% |
| Gongguoqiao | 291 | 29% | 72% |
| Miaowei | 291 | 32% | 87% |
| Dahuajiao | 291 | 33% | 81% |
| Huangdeng | 284 | 31% | 82% |
| Wunonglong | 284 | 28% | 76% |
| **Total** | **3004** | **26%** | **82%** |
Table S7. Quantitative comparison of Landsat-derived and altimetry-converted water surface area.

| Reservoir  | R (CC) | RMSE (km²) | NRMSE |
|------------|--------|------------|-------|
| Nuozhadu   | 0.994  | 13.941     | 0.049 |
| Xiaowan    | 0.977  | 9.901      | 0.062 |
| Huangdeng  | 0.977  | 1.884      | 0.077 |
| Jinghong   | 0.558  | 0.428      | 0.020 |

Table S8. The statistical indices of the annual peak and lowest discharge at Chiang Saen station for two periods: before and after the two biggest dams (Nuozhadu and Xiaowan) began operations.

|                  | Peak Discharge (cms) | Lowest Discharge (cms) |
|------------------|----------------------|------------------------|
|                  | Mean Q1 Median Q3    | Mean Q1 Median Q3      |
| 1990 - 2008      | 11157 9235 10700 12350 | 638 551 599 759        |
| 2013 - 2020      | 6476   5213 6834 7866  | 966 844 975 1077       |
| Change           | -45%  -45%  -43%  -42%  | 57%  69%  65%  42%     |
Figure S1. Comparison between Landsat-derived water level (green line), Jason altimetry water level (blue dots), and Sentinel-1-derived water level (orange dashed line) archived from Mekong Dam Monitor Platform for Nuozhadu (left) and Xiaowan (right) reservoirs. Note that Jason has a 10-day temporal resolution and Sentinel-1 have a frequency of up to 6 days (Sentinel-1A and B have a frequency of 12 days and interleave to each other). The comparison shows that the use of a monthly resolution yields the same trajectories of a weekly one.
Figure S2. E-A, A-S, and E-S curves of Bhumibol reservoir (top) and Ubol Ratana reservoir (bottom). The curves are represented by light blue lines, which are fitted to the data points (blue circles) derived from the DEM data. Note that the curves intersect the points identified by maximum water level, maximum water surface area, and full storage volume (dashed lines) as well as those identified by dead water level and dead storage volume (dotted lines). The green lines reported in panels (c) and (f) correspond to the observations by Electricity Generating Authority of Thailand (EGAT).
Figure S3. Water surface area (a,b) and storage variations (c,d) of Bhumibol reservoir (left) and Ubol Ratana reservoir (right). In panels (a,b), note the drastic difference in WSA values before (light blue points) and after (cyan points) the classification improvement. The corrected values of WSA are well in agreement with those converted from observed water level (EGAT) through E-A curves (blue dashed lines). In panels (c,d), note the similarity in the storage volume derived from Landsat images (cyan dotted lines) and observed data from EGAT (blue lines).
Figure S4. E-S curve of Nouzhadu (left) and Xiaowan (right) reservoirs obtained by using the trapezoidal approximation and direct calculation from the DEM.
Figure S5. Performance of three spectral indices (NDVI, NDWI, and MNDWI) in extracting the water surface area of Nuozhadu reservoir. Results are reported for three threshold values, 0, 0.05, and 0.1 and compared to the Maximum Water Extent dataset, developed by the European Commission’s Joint Research Centre (Pekel et al., 2016). The meaning of the three indices is explained in Table S5.
**Figure S6.** Performance of three spectral indices (NDVI, NDWI, and MNDWI) in extracting the water surface area of Xiaowan (top) and Manwan (bottom) reservoirs. Results are reported for three threshold values, 0, 0.05, and 0.1 and compared to the Maximum Water Extent dataset, developed by the European Commission’s Joint Research Centre (Pekel et al., 2016). The meaning of the three indices is explained in Table S5.
Figure S7. Performance of three spectral indices (NDVI, NDWI, and MNDWI) in extracting the water surface area of Jinghong (left) and Dachaoshan (right) reservoirs. Results are reported for three threshold values, 0, 0.05, and 0.1 and compared to the Maximum Water Extent dataset, developed by the European Commission’s Joint Research Centre (Pekel et al., 2016). The meaning of the three indices is explained in Table S5.
Figure S8. Performance of three spectral indices (NDVI, NDWI, and MNDWI) in extracting the water surface area of Gongguoqiao (left) and Dahuaqiao (right) reservoirs. Results are reported for three threshold values, 0, 0.05, and 0.1 and compared to the Maximum Water Extent dataset, developed by the European Commission’s Joint Research Centre (Pekel et al., 2016). The meaning of the three indices is explained in Table S5.
Figure S9. Performance of three spectral indices (NDVI, NDWI, and MNDWI) in extracting the water surface area of Miaowei (left), Huangdeng (middle) and Wunonglong (right) reservoirs. Results are reported for three threshold values, 0, 0.05, and 0.1 and compared to the Maximum Water Extent dataset, developed by the European Commission’s Joint Research Centre (Pekel et al., 2016). The meaning of the three indices is explained in Table S5.
**Figure S10.** Comparison of the simulated discharge by VIC-Res (blue dots) and observed discharge (grey line) at Chiang Sean for the period 2009-2019 (filling period of Xiaowan and Nuozhadu reservoirs). Observed data are archived from Mekong River Commission (MRC).

**Figure S11.** Comparison of storage derived from Landsat images and VIC-Res model for Nuozhadu (left) and Xiaowan (right) reservoirs.
Figure S12. E-A, A-S and E-S curves of Jinghong, Dachaoshan, Manwan and Gongguoqiao reservoir.
Figure S13. E-A, A-S and E-S curves of Miaowei, Dahuaqiao, Huangdeng and Wunonglong reservoir.
Figure S14. Water surface area of Huangdeng (top) and Jinghong (bottom) reservoirs. Note the drastic difference in WSA values before (lightblue points) and after (cyan points) the classification improvement. The corrected values of WSA are well in agreement with those obtained through altimetry water level data and E-A curves (dark blue points)
Figure S15. Storage variation of reservoirs on the Lancang River.
Figure S16. Operation curves of 8 reservoirs (Jinghong, Dachaoshan, Manwan, Gongguoqiao, Miaowei, Dahuaqiao, Huangdeng and Wunonglong).
**Figure S17.** Upper panel: graphical illustration of total storage and discharge at Chiang Saen station. Middle panel: wavelet analysis of the discharge. Colors represent wavelet power, while confidence level contours identify statistically significant power. The flow regime changed in 2014, when Nuozhadu reservoir started its normal operations. Bottom panel: wavelet coherency and phase between discharge and reservoir storage. Contours identify statistically significant coherencies. The vectors indicate the phase difference between discharge and storage.
References

Bonnema, M. and Hossain, F.: Inferring reservoir operating patterns across the Mekong Basin using only space observations, Water Resources Research, 53, 3791–3810, https://doi.org/10.1002/2016wr019978, 2017.

Do, P., Tian, F., Zhu, T., Zohidov, B., Ni, G., Lu, H., and Liu, H.: Exploring synergies in the water-food-energy nexus by using an integrated hydro-economic optimization model for the Lancang-Mekong River Basin, Science of The Total Environment, 728, 137996, https://doi.org/10.1016/j.scitotenv.2020.137996, 2020.

Duan, Z. and Bastiaanssen, W. G. M.: Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data, Remote Sensing of Environment, 134, 403–416, https://doi.org/10.1016/j.rse.2013.03.010, 2013.

Gao, H., Birkett, C., and Lettenmaier, D. P.: Global monitoring of large reservoir storage from satellite remote sensing, Water Resources Research, 48, w09 504, https://doi.org/10.1029/2012wr012063, 2012.

Pekel, J.-F., Cottam, A., Gorelick, N., and Belward, A. S.: High-resolution mapping of global surface water and its long-term changes, Nature, 540, 418–422, https://doi.org/10.1038/nature20584, 2016.

Zhai, K., Wu, X., Qin, Y., and Du, P.: Comparison of surface water extraction performances of different classic water indices using OLI and TM imageries in different situations, Geospatial Information Science, 18, 34–42, https://doi.org/10.1080/10095020.2015.1017911, 2015.