
Christian Schwatke, Daniel Scherer, Denise Dettmering

Deutsches Geodätisches Forschungsinstitut Technische Universität München (DGFI-TUM)
Monitoring and modeling of the Earth's water cycle has become increasingly important in the last years, especially in the context of climate change.

The number of in-situ stations has been decreasing since 1980 (see GRDC).

The knowledge about storage changes (which cannot be measured directly) is of great importance for the development of hydrological models.

Remote sensing has the potential to monitor water levels and surface areas in order to estimate storage changes also in remote areas.

Water levels can be derived from satellite altimetry.

DGFI-TUM maintains the "Database for Hydrological Time Series of Inland Waters" (DAHITI) which provides more than 1700 water level time series from satellite altimetry for inland waters.

Radar or optical images can be used to retrieve surface information.

In this study, a new tool "Automated Water Area Extraction Tool" (AWAX) has been developed in order to extract monthly water masks and area extents using optical imagery from Landsat and Sentinel-2.
<table>
<thead>
<tr>
<th>Mission</th>
<th>Repeat Cycle</th>
<th>Period</th>
<th>Resolutions (Bands)</th>
<th>Quality Band</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat-4 (MSS, TM)</td>
<td>16 days</td>
<td>1982-08-24 – 1993-12-14</td>
<td>30m (R,G,B,N,S1,S2)</td>
<td>CFMASK</td>
<td>L2 (TOA)</td>
</tr>
<tr>
<td>Landsat-5 (MSS, TM)</td>
<td>16 days</td>
<td>1984-01-01 – 2012-05-05</td>
<td>30m (R,G,B,N,S1,S2)</td>
<td>CFMASK</td>
<td>L2 (TOA)</td>
</tr>
<tr>
<td>Landsat-7 (ETM+)</td>
<td>16 days</td>
<td>1999-01-01 – active</td>
<td>30m (R,G,B,N,S1,S2)</td>
<td>CFMASK</td>
<td>L2 (TOA)</td>
</tr>
<tr>
<td>Landsat-8 (OLI, TIRS)</td>
<td>16 days</td>
<td>2013-04-11 – active</td>
<td>30m (R,G,B,N,S1,S2)</td>
<td>CFMASK</td>
<td>L2 (TOA)</td>
</tr>
<tr>
<td>Sentinel-2A (MSI)</td>
<td>10 days</td>
<td>2015-06-23 – active</td>
<td>10m (R,G,B,N), 20m (S1,S2)</td>
<td>FMASK4</td>
<td>L1B (BOA)</td>
</tr>
<tr>
<td>Sentinel-2B (MSI)</td>
<td>10 days</td>
<td>2017-03-07 – active</td>
<td>10m (R,G,B,N), 20m (S1,S2)</td>
<td>FMASK4</td>
<td>L1B (BOA)</td>
</tr>
</tbody>
</table>
Methodology

Major processing steps:

Flowchart of AWAX-Approach

- Initialization of Area of Interest (AOI)
- Pre-Processing
  - Calculate Water Indexes
  - Thresholding
  - Create Monthly Mask with Gaps

- All months processed?
  - Yes: Export Results
  - No: Monthly Masks with Gaps

- Compute Long-Term Water Probability Mask

- Calculate Threshold of Water Probability
  - Fill Gaps
  - Export Results
  - Surface Area in km²

- Calculate Surface Area Time Series

- All months processed?
  - Yes: Filled Monthly Masks
  - No: Surface Area Time Series
Methodology

Major processing steps:

- Initialization of AOI
Methodology

Major processing steps:

- Initialization of AOI
- Creation of monthly land-water masks (with data gaps)
Methodology

Major processing steps:

- Initialization of AOI
- Creation of monthly land-water masks (with data gaps)
- Computation of long-term water probability mask

Flowchart of AWAX-Approach
Methodology

Major processing steps:

• Initialization of AOI
• Creation of monthly land-water masks (with data gaps)
• Computation of long-term water probability mask
• Filling data gaps
Methodology

Major processing steps:

• Initialization of AOI
• Creation of monthly land-water masks (with data gaps)
• Computation of long-term water probability mask
• Filling data gaps
• Calculation of surface area time series
Initialization of Area of Interest (AOI)

**Ray Roberts, Lake, Texas, USA**
- Surface Area: ~119 km²
- Water Level: 190 – 196 m
- Type: Reservoir

**Coarse Boundary**
- Automated Data Extraction

**Reference Location**
- Automated Target Selection
Data Extraction

Creation of monthly composite images

Google Earth Engine (Landsat-4, -5, -7, -8)
  ↓
Download Monthly Composite
  ↓
Resample and Reproject Images
  ↓
Band-Wise Merging
  ↓
RED  GREEN  BLUE  NIR  SWIR1  SWIR2  QUALITY

Copernicus Open Access Hub (Sentinel-2A, -2B)
  ↓
Download Daily Scenes
  ↓
Create Quality Band
  ↓
Create Monthly Composite
  ↓
Resample and Reproject Images

(a) Sentinel-2A (2016-04-02)
(b) Sentinel-2A (2016-04-15)
(c) Landsat-7 (2016-04-25)
(d) Composite (2016-04)

Figure 4. Used daily scenes from Landsat and Sentinel-2 and resulting composite image for Lake Ray Roberts in April 2016. Data gaps in the composite image are highlighted in yellow.
Data Extraction

Used Bands ...

Near-Infrared (NIR)

Red

Green

Blue

Short Wave Infrared 1 (SWIR1)

Short Wave Infrared 2 (SWIR2)

Quality-Band
Calculation of Water-Indexes

- **Modified Normalized Difference Water Index (MNDWI)**
  
  \( \text{MNDWI} \) 

  \((\text{Xu}, 2006)\)

- **New Water Index (NWI)**
  
  \( \text{NWI} \) 

  \((\text{Li}, 2016)\)

- **Automated Water Extraction Index for Non-Shadow Areas (AWEI}_{\text{nsh}}\)**
  
  \((\text{Feyisa et al, 2014})\)

- **Automated Water Extraction Index for Shadow Areas (AWEI}_{\text{sh}}\)**
  
  \((\text{Feyisa et al, 2014})\)

- **Tasseled Cap for Wetness (TC}_{\text{wet}}\)**
  
  \((\text{Crest, 1985})\)
Land-Water Classification
Land-Water Classification

Initialization MNDWI

MNDWI

NWI

AWEIsh

AWEInsh

TCwet

Histogram

Cumulative Histogram

Histogram

Cumulative Histogram

Histogram

Cumulative Histogram

Histogram

Cumulative Histogram

Histogram

Cumulative Histogram

Histogram

Cumulative Histogram

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Cumulative Histogram

C. Schwatke | 27th IUGG General Assembly | Montréal, Canada | 08-18 July 2019
Creation of binary monthly land-water masks with data gaps

<table>
<thead>
<tr>
<th>Input Value (based on 5 water indexes)</th>
<th>Monthly Land-water mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Water Indexes</td>
<td>Water (1)</td>
</tr>
<tr>
<td>4 Water Indexes</td>
<td>Water (1)</td>
</tr>
<tr>
<td>3 Water Indexes</td>
<td>Data Gap</td>
</tr>
<tr>
<td>2 Water Indexes</td>
<td>Data Gap</td>
</tr>
<tr>
<td>1 Water Indexes</td>
<td>Land (0)</td>
</tr>
<tr>
<td>0 Water Indexes</td>
<td>Land (0)</td>
</tr>
<tr>
<td>Data Gap</td>
<td>Data Gap</td>
</tr>
</tbody>
</table>
Long-Term Water Probability Mask

- All monthly land-water masks (with data gaps) are merged in order to compute a long-term water probability mask
- Finally, the reference point from the initialization step is used to select the area of interest (AOI)
Fill Data Gaps

1. Create dependency between surface area and water probability mask
Fill Data Gaps

1. Create dependency between surface area and water probability mask
2. Merge land water mask (with gaps) and water probability mask
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3. Calculate initial surface area $A_{\text{initial}}$ (46.85 km²)
Fill Data Gaps

1. Create dependency between surface area and water probability mask
2. Merge land water mask (with gaps) and water probability mask
3. Calculate initial surface area $A_{\text{initial}}$ (46.85 km²)
4. Iterative filling of data gaps $A_{\text{fill}}$ ($p = 45\% \rightarrow 61.01$ km²)
1. Create dependency between surface area and water probability mask
2. Merge land water mask (with gaps) and water probability mask
3. Calculate initial surface area $A_{\text{initial}}$ (46.85 km²)
4. Iterative filling of data gaps $A_{\text{fill}}$ (p = 45% → 61.01 km²)
5. Merge initial and fill masks to get gap-free mask $A(45\%) = 107.86$ km²
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Ray Roberts, Lake (USA)

• AOI: 137.38 km²
• 290 valid masks (1984 - 2018)
• Fill Area:
  • Max: 51.58 km² (37.5 % of AOI)
  • Avg: 2.18 km² (1.6 % of AOI)
Results / Validation

Ray Roberts, Lake (USA)

- Improvement of $R^2$ from 0.777 to 0.934 (in-situ), respectively 0.910 (altimetry)
- Cross-validation leads to a RMSE of 2.85 km² (2.07% of AOI)
Results / Validation

Poco da Cruz, Reservoir (Brazil)

- AOI: 58.07 km²
- 228 valid masks (1984 - 2018)
- Fill Area:
  - Max: 25.95 km² (44.7 % of AOI)
  - Avg: 3.23 km² (5.6 % of AOI)
Results / Validation

- **Poco da Cruz, Reservoir** (*Brazil*)

- Improvement of $R^2$ from 0.921 to 0.981 (in-situ), respectively 0.977 (altimetry)
- Cross-validation leads to a RMSE of 1.10 km² (1.9 % of AOI)
Results / Validation

Tharthar, Lake (Iraq)

- AOI: 2491.37 km²
- 327 valid masks (1984 - 2018)
- Fill Area:
  - Max: 657.92 km² (44.7 % of AOI)
  - Avg: 67.80 km² (2.7 % of AOI)
Results / Validation

Tharthar, Lake *(Iraq)*

- Improvement of $R^2$ from 0.717 to 0.989 (altimetry)
- Cross-validation leads to a RMSE of 16.71 km² (0.7 % of AOI)
In this study, 32 globally distributed lakes and reservoirs have been investigated

- **Surface area**: 9.84 – 2491.37 km²
- **Water level variations**: 2.26 – 43.56 m
- **Annual cloud coverage**: 22 – 65 %
- **Annual rainfall**: 71 – 1749 mm/y

**Quality Assessment**

- **Improvements of R² between initial and filled surface areas**
  - 0.037 – 0.441 using in-situ data
  - 0.014 – 0.734 using satellite altimetry (DAHITI)
  - Final correlations R² have been increased to more than 0.8 or even 0.9 for almost all study areas.

- **Average surface area errors from cross-validation**
  - 0.30 km² - 67.80 km² (0.89 % - 9.68 % of AOI)
Optical images from Landsat-4/-5/-7/-8 and Sentinel-2A/2B are used for creation of monthly composites.

A new approach for the estimation of monthly land-water masks based on the combination of five water indexes (MNDWI, NWI, AWEI$_{sh}$, AWEI$_{nsh}$, TC$_{wet}$) and a new threshold computation has been demonstrated.

More than 30 years of monthly masks are merged in order to calculate a long-term water probability mask.

Remaining data gaps are filled successfully by using the long-term water probability mask.

The average correlation coefficients $R^2$ between surface areas and water levels increased from 0.611 to 0.862 after filling data gaps which is an improvement of about 41%.

This new product has the potential for new applications:
- Densification of water level time series in combination with land water masks (talk today morning)
- Volume storage variations of lakes and reservoirs in combination with satellite altimetry
- Estimation of river discharge by remote sensing (optical imagery and satellite altimetry)