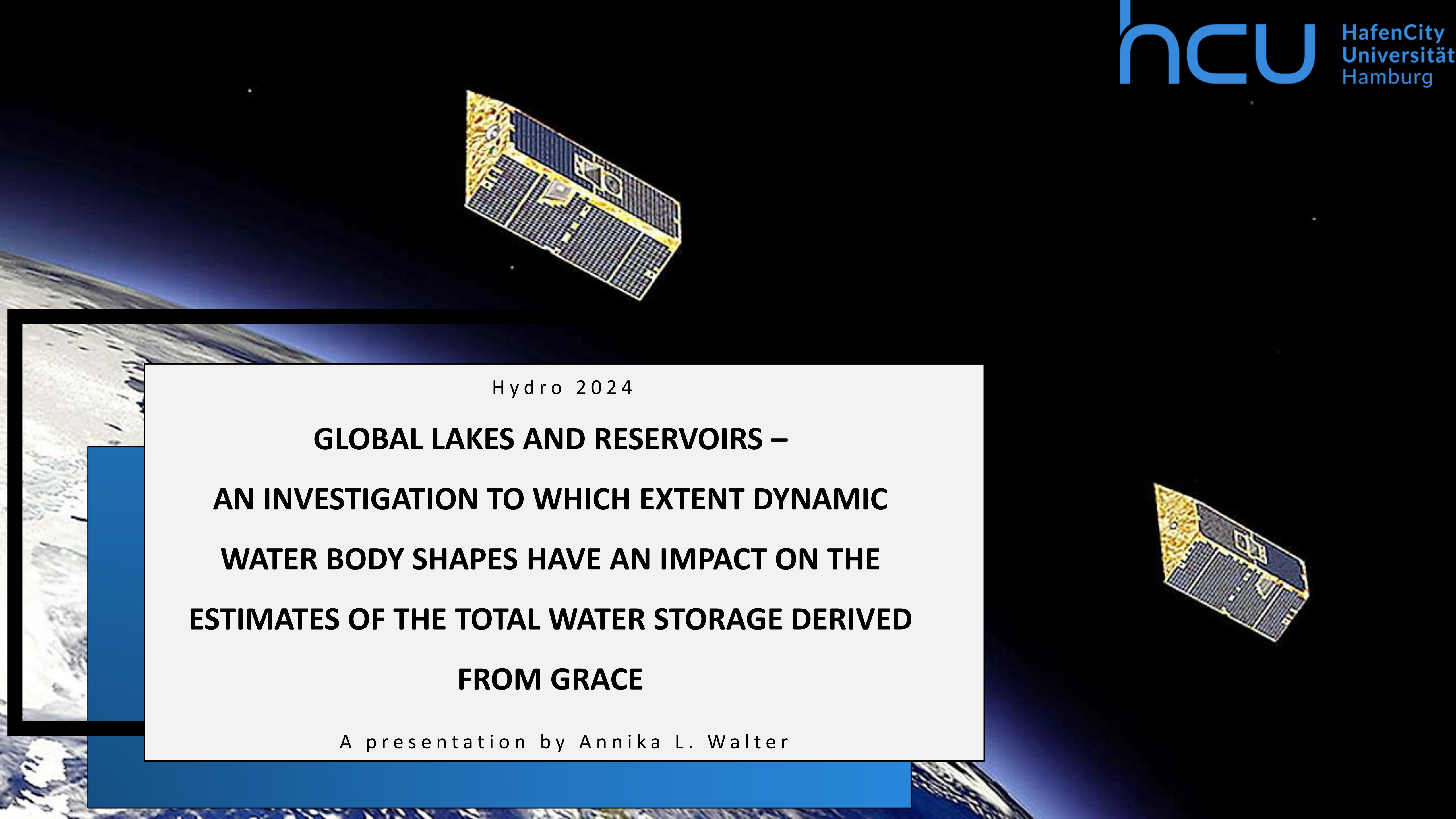


Hydro 2024

GLOBAL LAKES AND RESERVOIRS –
AN INVESTIGATION TO WHICH EXTENT DYNAMIC WATER BODY SHAPES HAVE AN IMPACT ON THE ESTIMATES OF THE TOTAL WATER STORAGE DERIVED FROM GRACE

A presentation by Annika L. Walter

HafenCity Universität Hamburg

Introduction - Hydrological Models

- Information of storage compartments + flow patterns

  -> limitation of available data

  +

  -> simplification of processes

  =

  -> limited reliability

- Independent observations

  -> Gravity Recovery and Climate Experiment (GRACE)

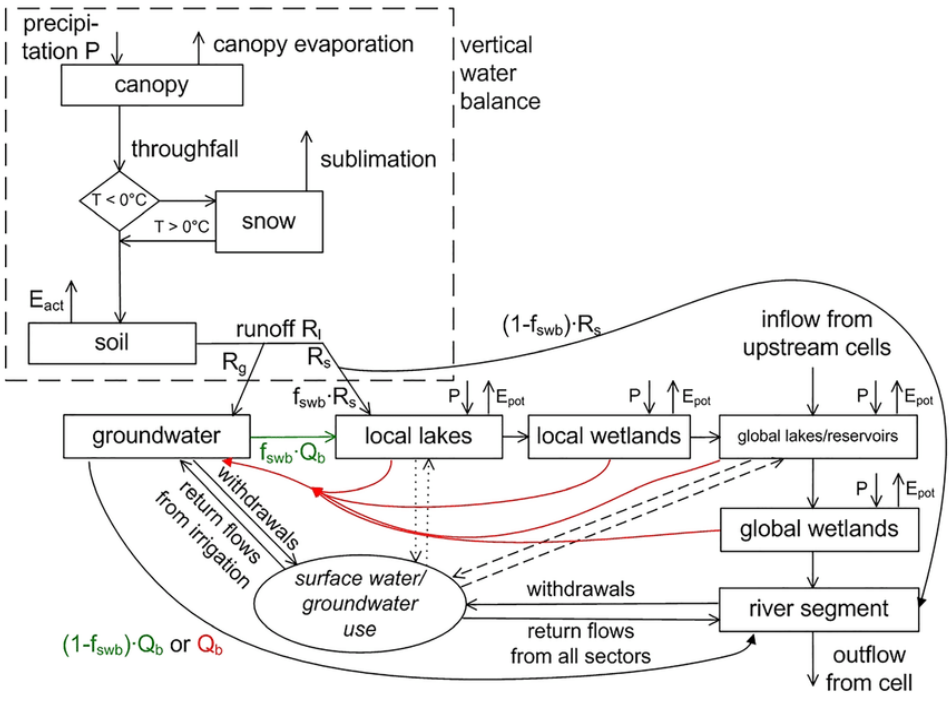


Figure 1: Schematic overview of the WaterGAP model

Introduction - GRACE

- GRACE observes the total water storage

  = sum of all water storage compartments

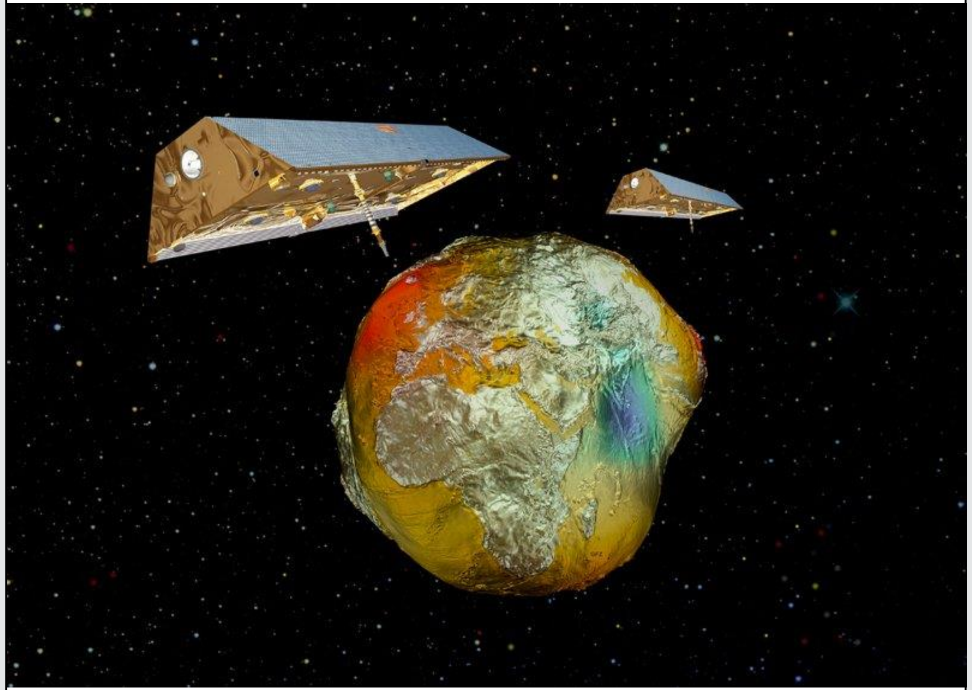


Figure 2: Satellite Mission GRACE

Introduction - GRACE

- GRACE observes the total water storage

  = sum of all water storage compartments

  - many hydrological models do not contain an inland surface water storage compartment

  -> mass changes of surface water bodies distort other storage compartments

  -> focus of interest might be groundwater related mass changes

  -> separation of the GRACE signal

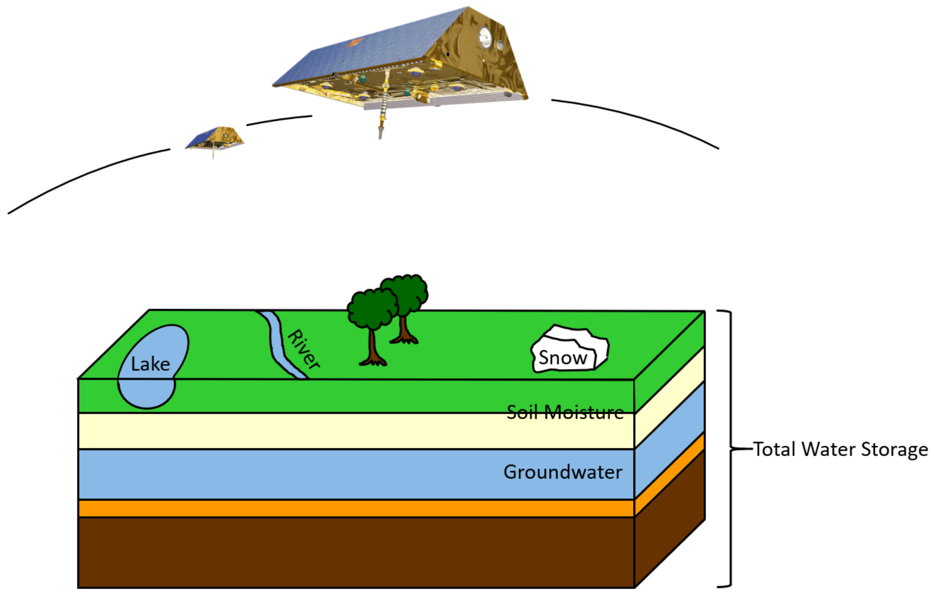


Figure 3: Total Water Storage

Introduction - GRACE

1: Subtract available reference data

2: Decompose the signal

Introduction - GRACE

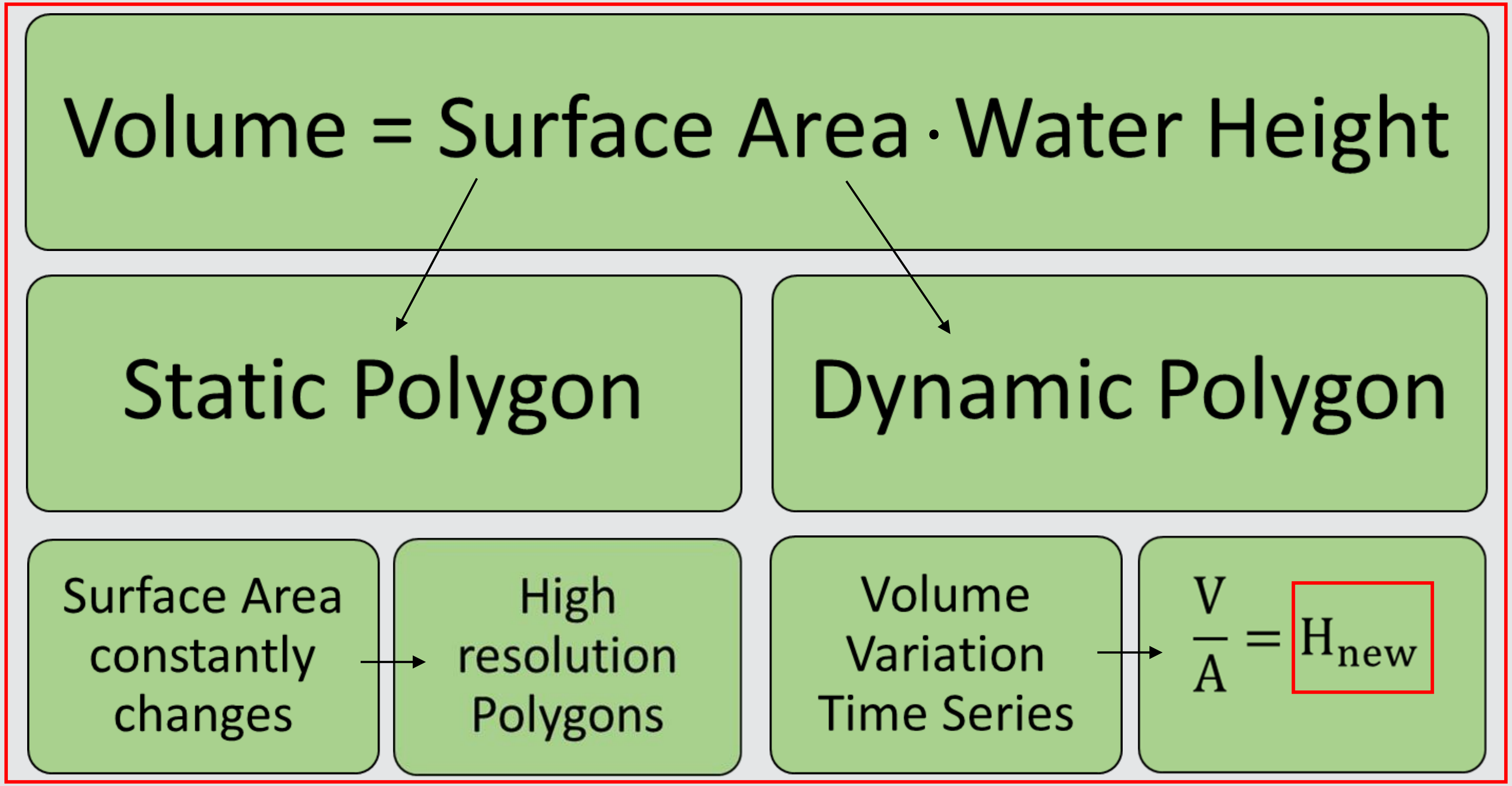
1: Subtract available reference data

- Approximate the volume of water bodies

GRACE Signal – (approximated volume · density) = GRACE signal without the mass variation of the water body

- Volume = Surface Area · Water Height

Introduction - GRACE



Data Bases

Shoreline Polygons from the Global WaterPack project

- Optical satellite images
  Daily water masks
  -> vectorized -> polygon
- Access to one polygon per surface water body

Water Level Time Series from DAHITI

- Database for Hydrological Time Series of Inland Waters
- Satellite altimetry

Volume Variation Time Series from DAHITI

- Surface area extent
  -> optical satellite images
- Water level values
  -> satellite altimetry data

Pre-processing

Pre-processing

- Averaging to monthly mean value
- Closing of data gaps by a linear interpolation
- Investigation period from 01/2003 to 12/2016
- Reduction by mean value
- Division of the volume variation time series by the surface area extent of the static polygons

python™

Figure 4: Python

Pre-processing

- Discretise the surface polygon to a fine-resolution grid of 0.0025 ° x 0.0025 °
- Surface Area Extent · Water level

  -> Water level values from DAHITI (static)

  -> Water level values computed from volume variation time series (dynamic)
- Lower resolution grid of 0.5 ° x 0.5 °

  -> water level anomaly of each grid cell

  -> forward modelling algorithm

GROOPS

Gravity Recovery Object Oriented Programming System

Figure 5: GROOPS

Forward - Modelling

- Resolution of the surface water variations <-> spatial resolution of GRACE

  -> Forward modelling procedure

  -> Water level anomaly values have to be expanded into spherical harmonic coefficients

Spherical harmonic coefficients with degree (n) and order (m)

Radius of the Earth

Load Love Numbers

Change of the water storage with co-latitude (θ) and longitude (λ)

$$\begin{bmatrix}\Delta C_{nm}\\ \Delta S_{nm}\end{bmatrix} = \frac{R^2}{M} \cdot \frac{k_n+1}{2n+1} \int_0^{\pi} \int_0^{2} \left(\Delta TWS(\theta,\lambda) \cdot P_{nm}(\cos\theta) \begin{bmatrix}\cos m(\lambda)\\ \sin m(\lambda)\end{bmatrix} \cdot \sin(\theta) \right) \cdot d\lambda \cdot d\theta$$

Mass of the Earth

Legendre functions

Equation 1: Spherical Harmonic Coefficients

Filtering

- DDK3 Filter
- Forward modelled and filtered spherical harmonic potential coefficients express the signal that GRACE would measure, if the observations were only influenced by the changing mass of the respective water body
- Grid-based solution

  -> Re-computation

Re-computation

Total Water Storage after filtering for every grid cell

Mass of the Earth

Legendre functions

$$\Delta TWS^F(\theta,\lambda) = \frac{M}{4\pi R^2 \rho} \sum_{n=0}^{96} \sum_{m=0}^{n} \left(\frac{2n+1}{1+k_n} \cdot P_{nm}(\cos\theta) \cdot \left(\Delta C_{nm}^F \cos(m\lambda) + \Delta S_{nm}^F \sin(m\lambda)\right) \right)$$

Filtered Spherical Harmonic Coefficients

Load Love numbers

Density of the Water

Radius of the Earth

Equation 2: Total Water Storage for every grid cell after filtering

Results

- 29 water bodies

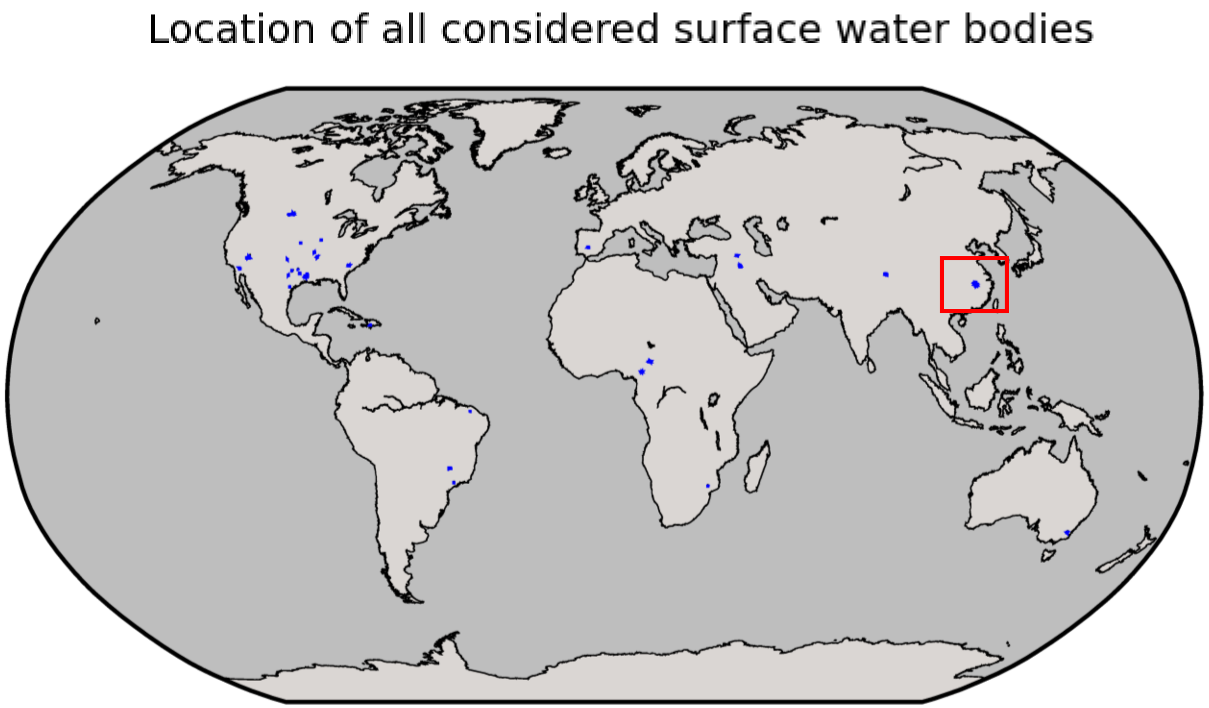


Figure 6: Map of all 29 considered surface water bodies

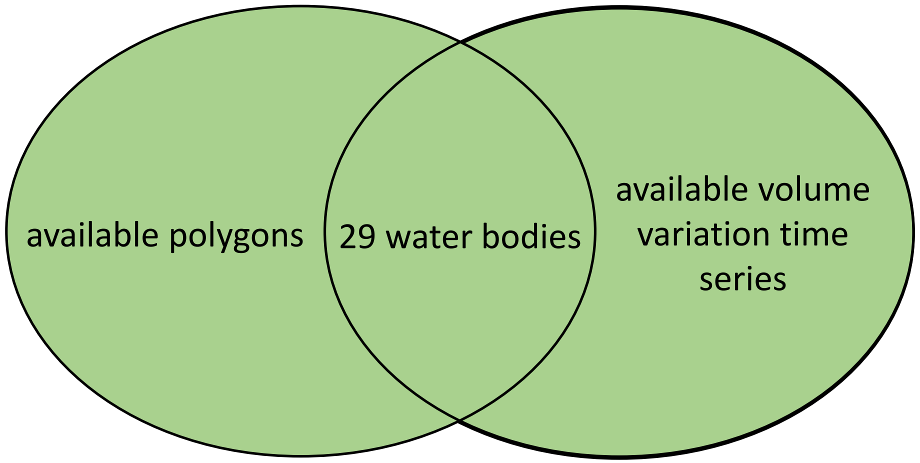


Figure 7: Venn - Diagram

Results - Lake Poyang

- Process of subtraction = Removal Correction (computed for every single grid cell)

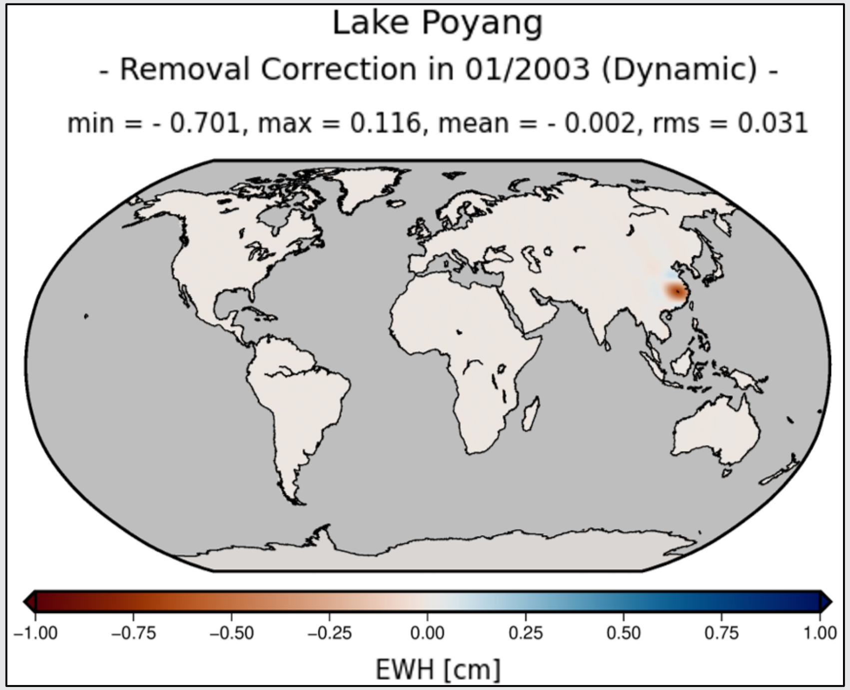


Figure 8: Removal correction (Dynamic) in 01/2003 for the Lake Poyang

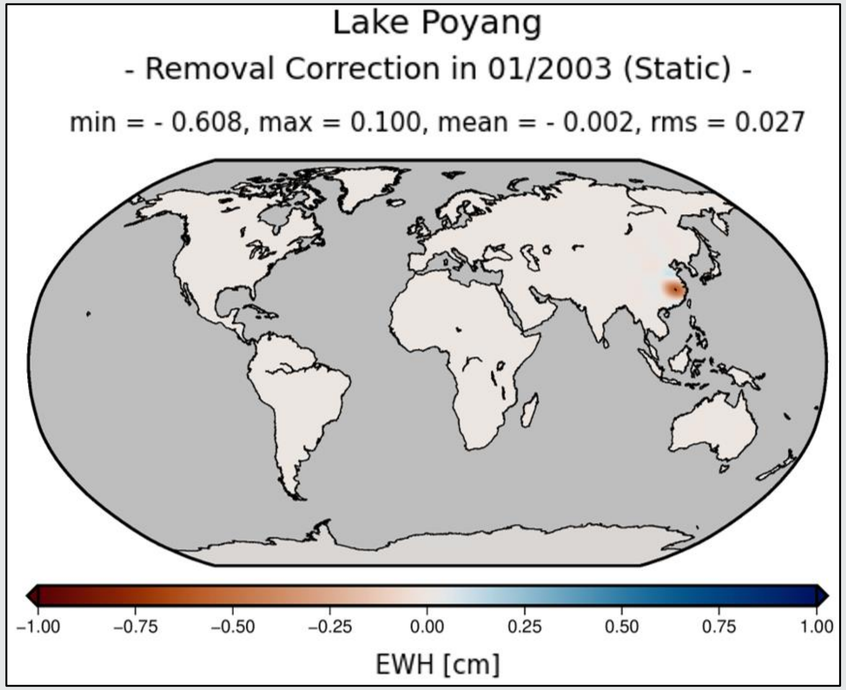


Figure 9: Removal correction (Static) in 01/2003 for the Lake Poyang

Results - Lake Poyang

- Peaks -> precipitation is closely linked to the east Asian Monsoon (April -> June)
- GRACE delivers column - integrated data

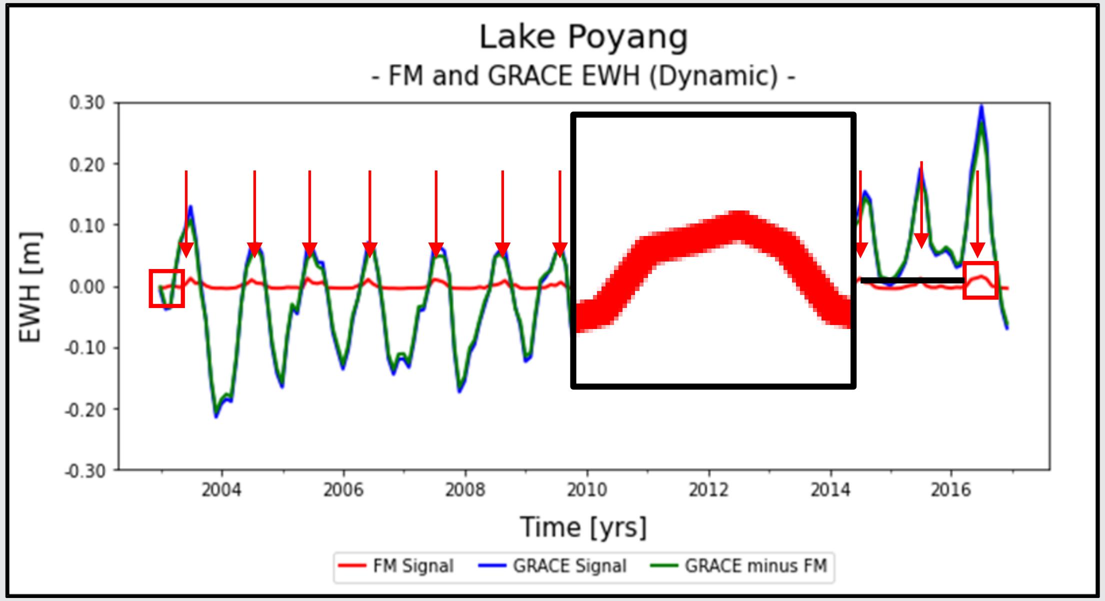


Figure 10: FM, GRACE and GRACE-FM EWH (Dynamic) for the Lake Poyang

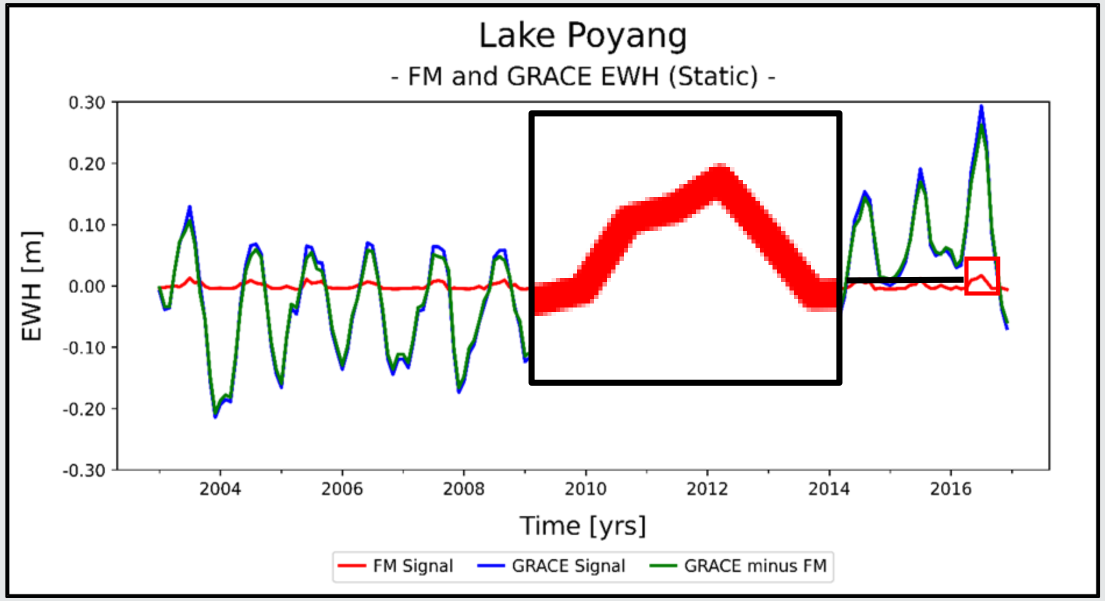


Figure 11: FM, GRACE and GRACE-FM EWH (Static) for the Lake Poyang

Results - Lake Poyang

- Differences are in the range of sub-millimetres

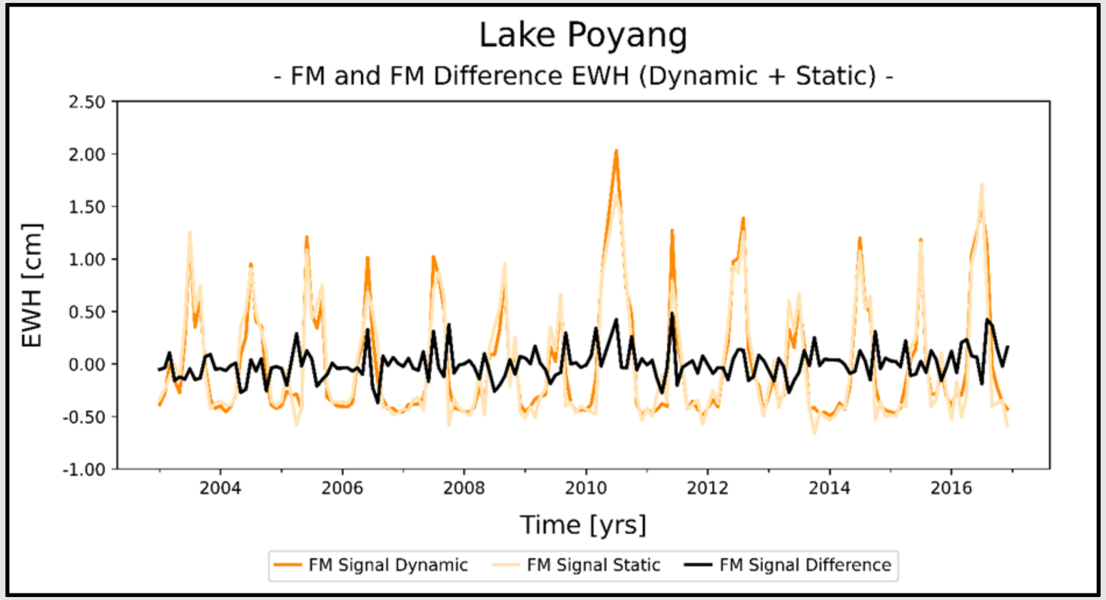


Figure 12: FM and FM difference EWH (Dynamic and Static) for the Lake Poyang

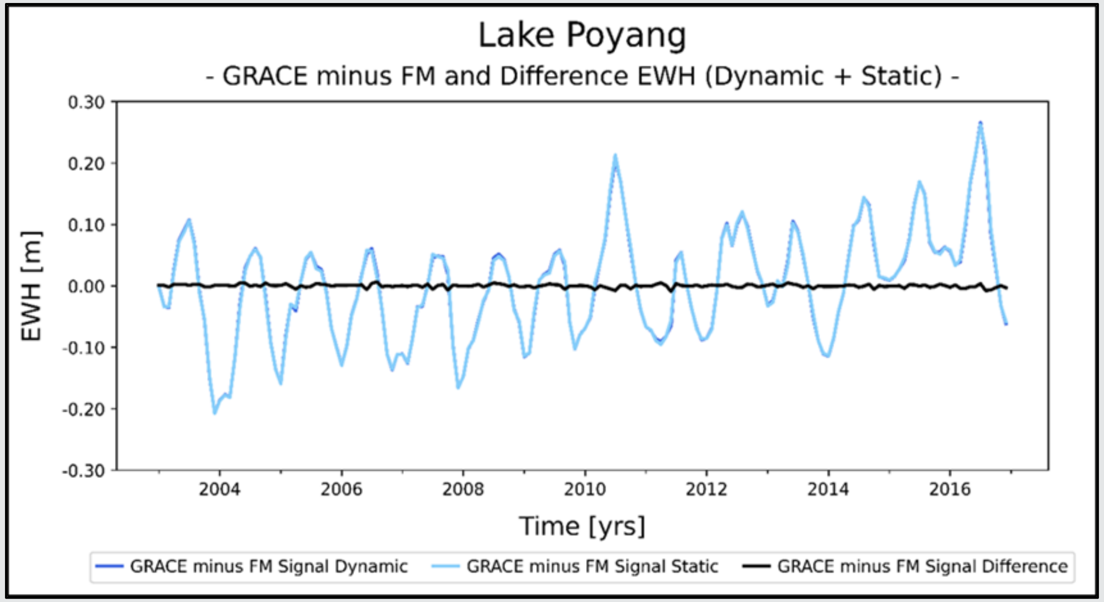


Figure 13: GRACE - FM and Difference EWH (Dynamic and Static) for the Lake Poyang

Results - Lake Poyang

- GRACE flies in an average altitude of approx. 450 km
- The scale has to be adjusted

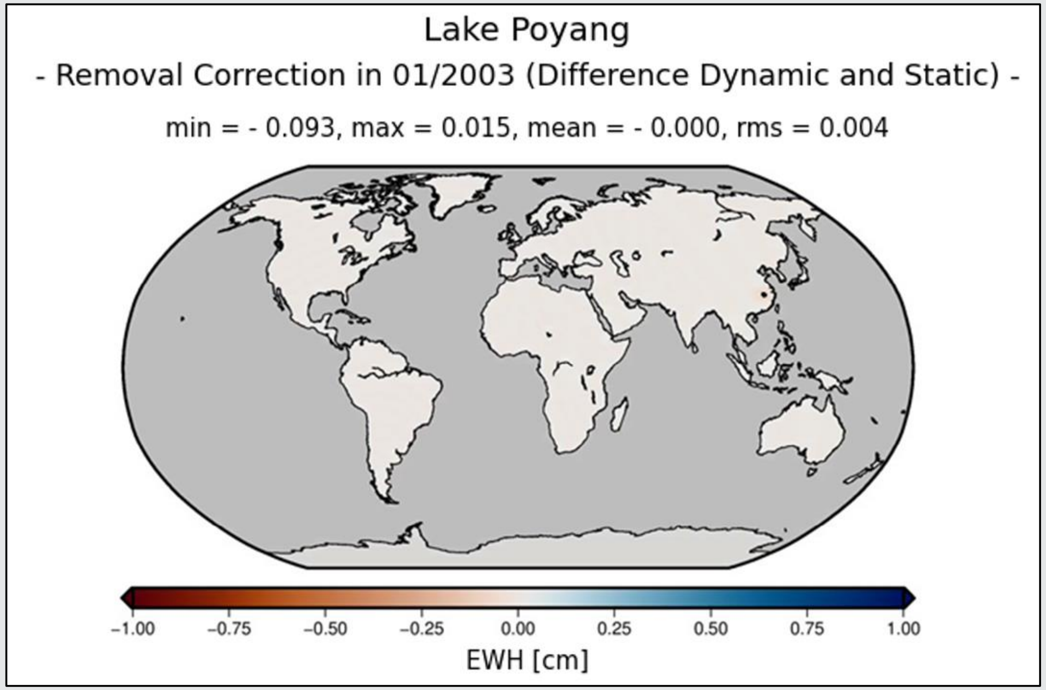


Figure 14: Removal correction (Difference) in 01/2003 for the Lake Poyang

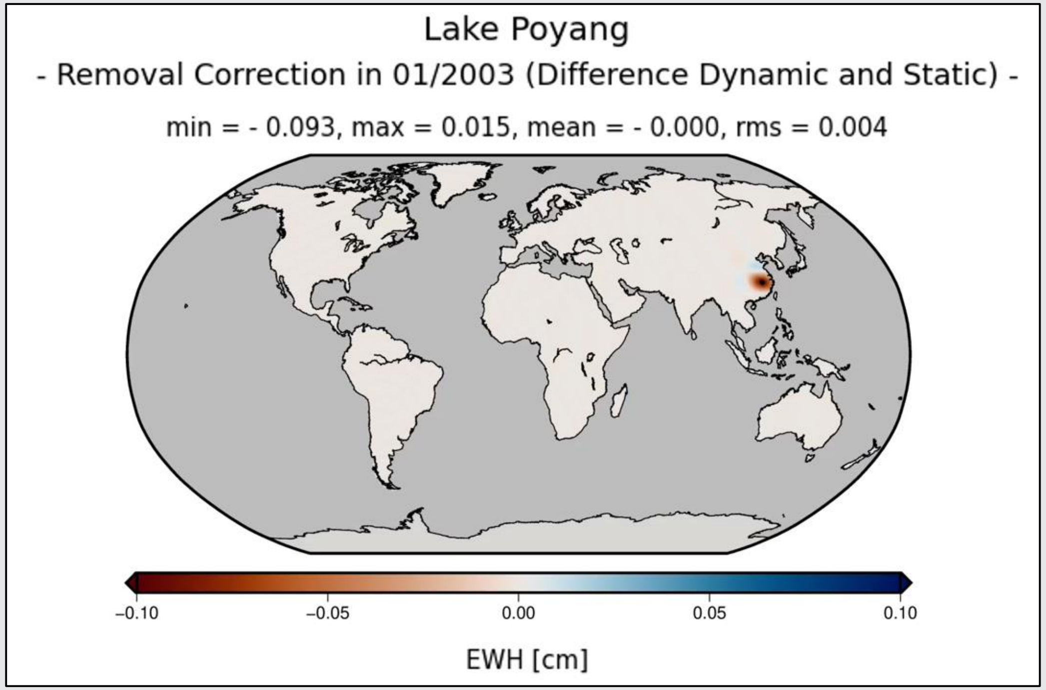


Figure 15: Removal correction (Difference) in 01/2003 for the Lake Poyang with adjusted scale

Results - All water bodies

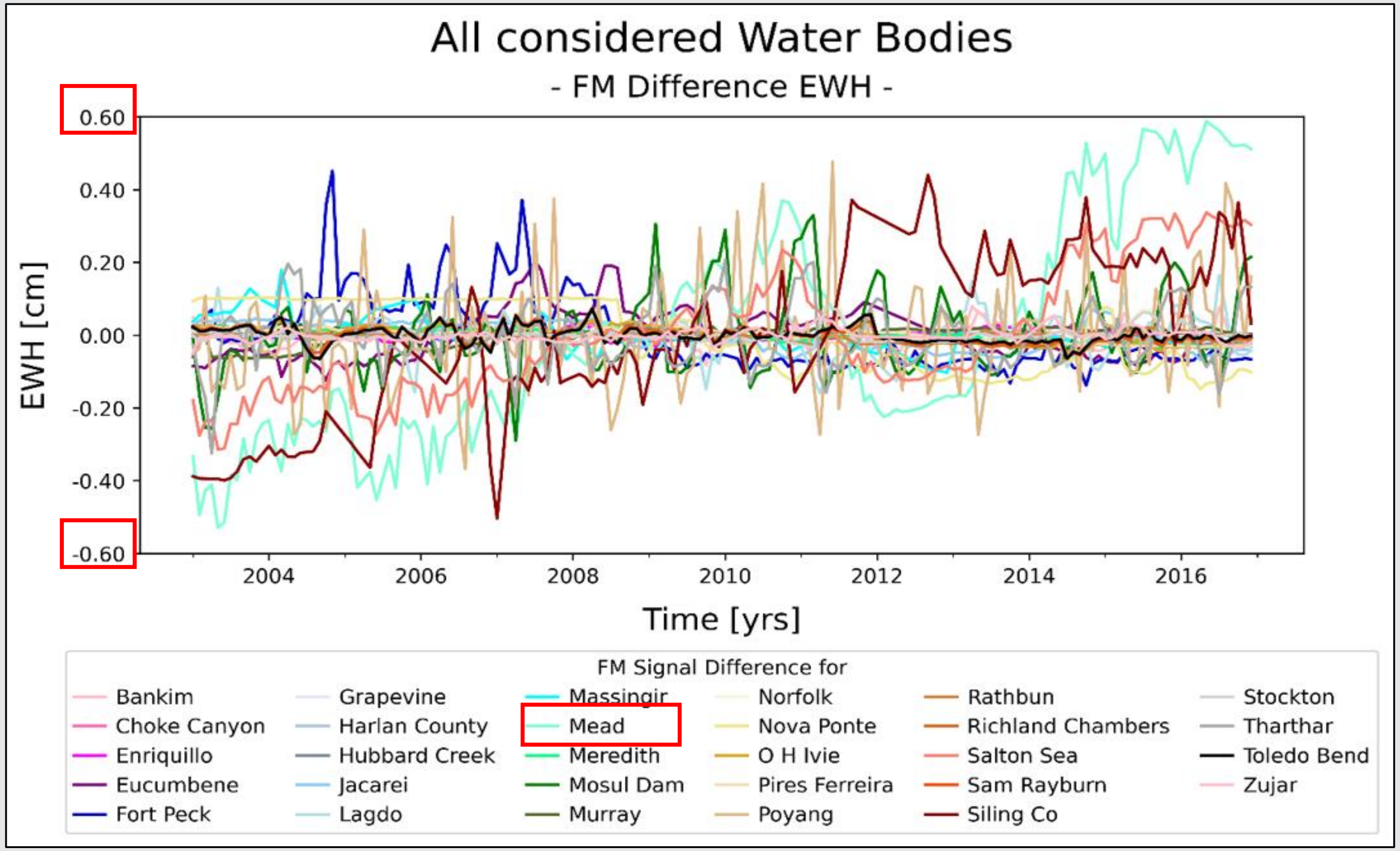


Figure 16: FM difference EWH for all considered water bodies

Results - All water bodies

mean value

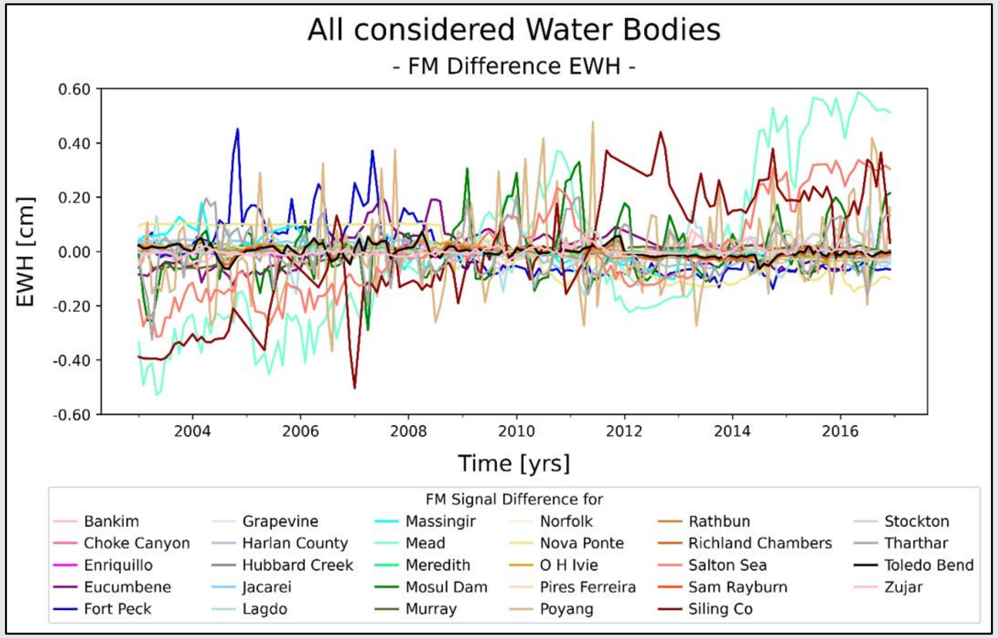


Figure 17: FM difference EWH for all considered water bodies

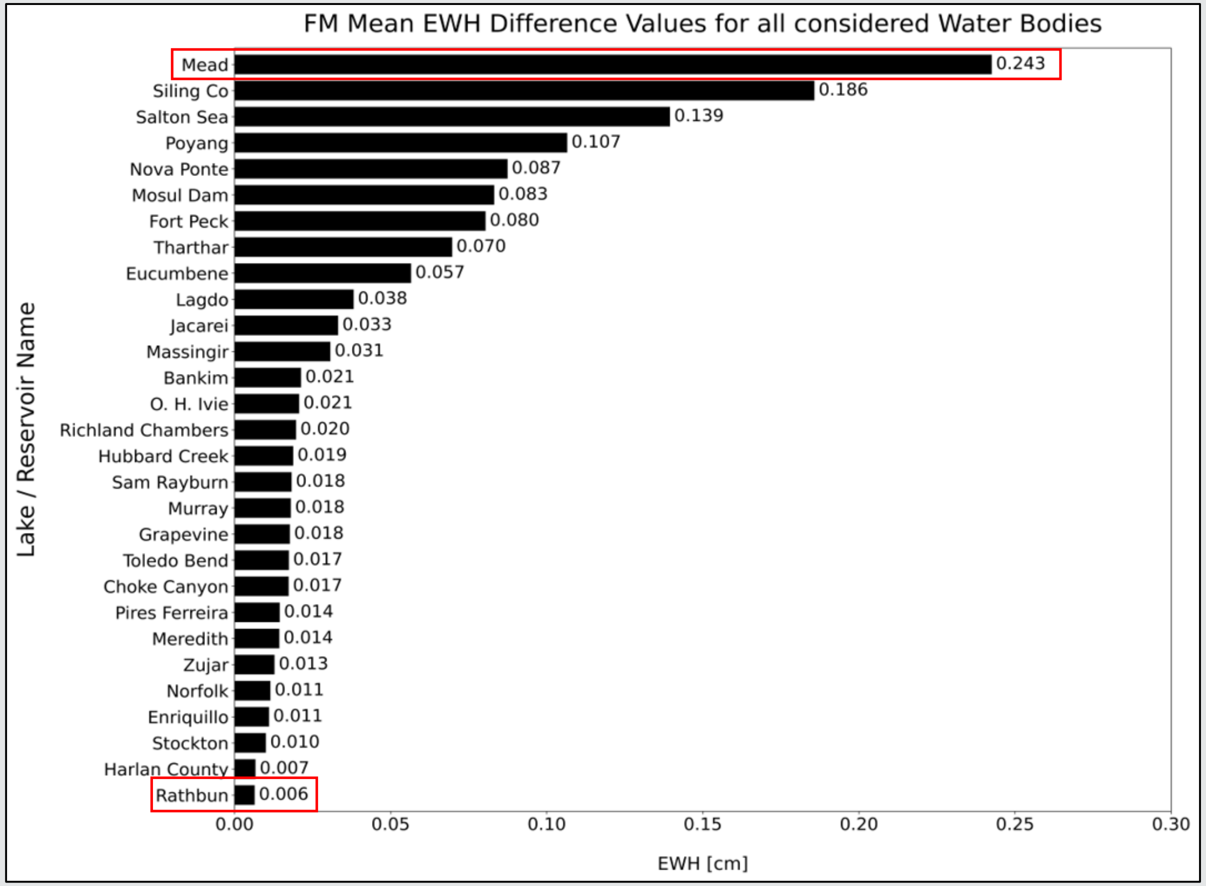


Figure 18: FM Mean EWH Difference values for all considered water bodies

Results - driving factors

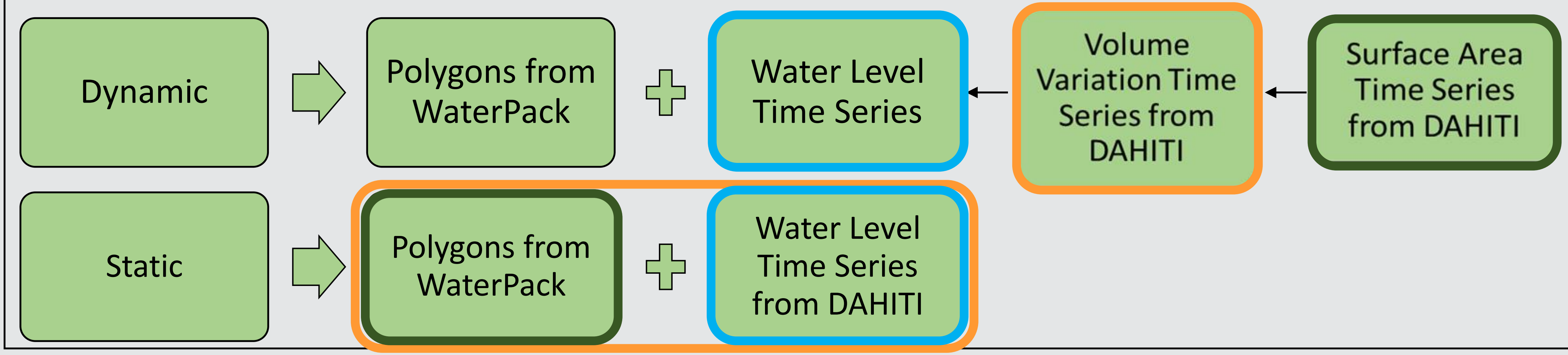
- Lake Mead does not have any specific features

≠ largest water body

≠ largest volume variation / volume variation difference

-> input parameters

-> large difference (input parameters) -> large deviation (results) -> large difference (removal correction)



Results - driving factors

- Lake Mead does not have any specific features

≠ largest water body

≠ largest volume variation / volume variation difference

-> input parameters

-> large difference (input parameters) -> large deviation (results) -> large difference (removal correction)

-> Neither a direct linear relationship, nor a tendency between the difference of the input parameters and the different results caused by the usage of dynamic and static water body shapes

Conclusion

- Reciprocally acting characteristics
- Consistently marginal influence

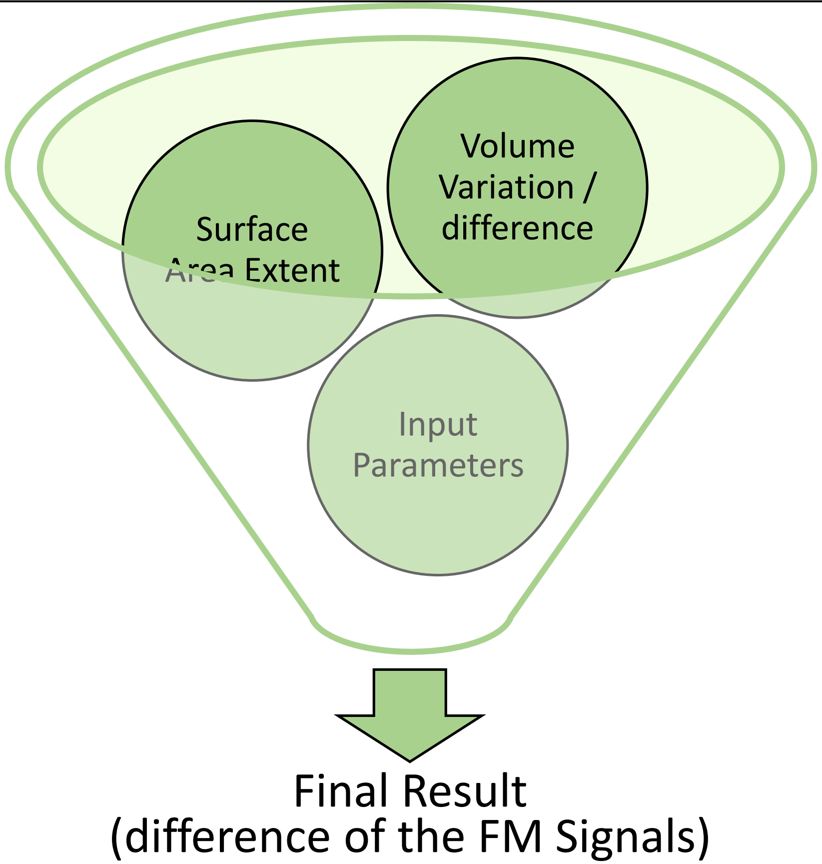


Figure 19: Driving Factors

Conclusion

- Reciprocally acting characteristics
- Consistently marginal influence
- Difference in the range of sub-millimetres could be detected for every single water body

  -> consideration of dynamic water body shapes does make a difference

  -> difference is reflected in the corrected GRACE signal (hydrological models)
- Supposedly non-significant differences will add up
- Requirements of the end product: client + user

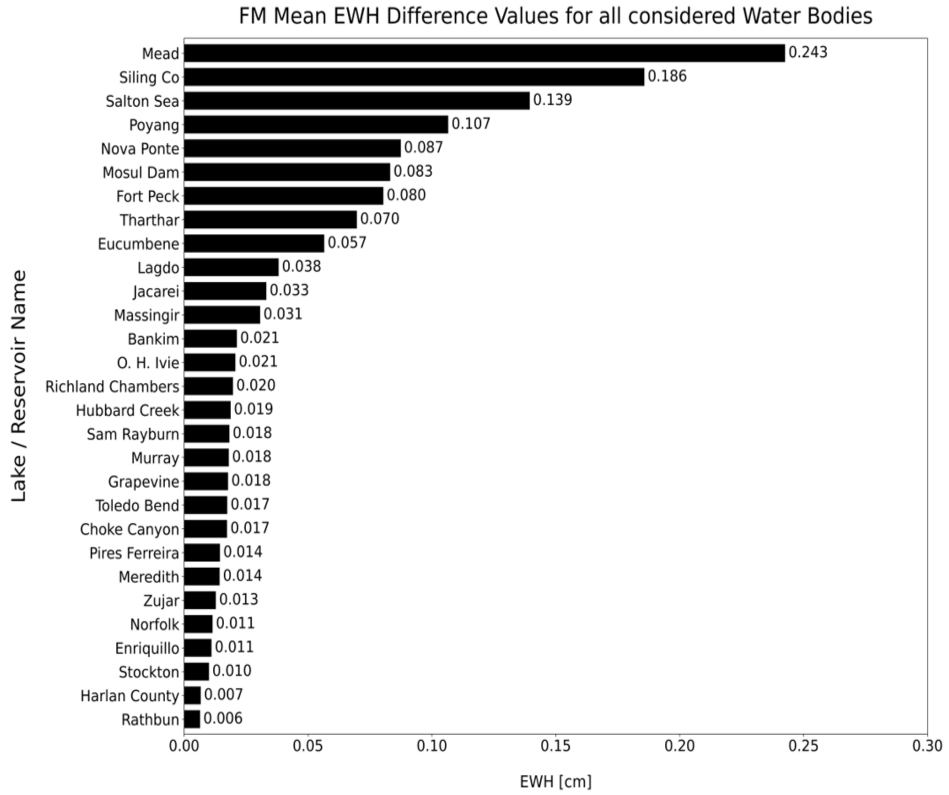


Figure 20: FM Mean EWH Difference values for all considered water bodies

Discussion and Outlook

- Investigated Water Bodies have a comparably small size
- Spatial resolution of 300 km to 400 km vs 21 / 29 < 500 km²

  -> usage of the corrected GRACE data for the purpose of hydrological models is questionable

  -> resilience of the obtained results is further limited
- Focus on Lakes and Reservoirs ≠ Rivers

  -> more sophisticated data assimilation strategies

  -> improve quality + credibility of hydrological models
- Hydrological models will gain increasingly importance

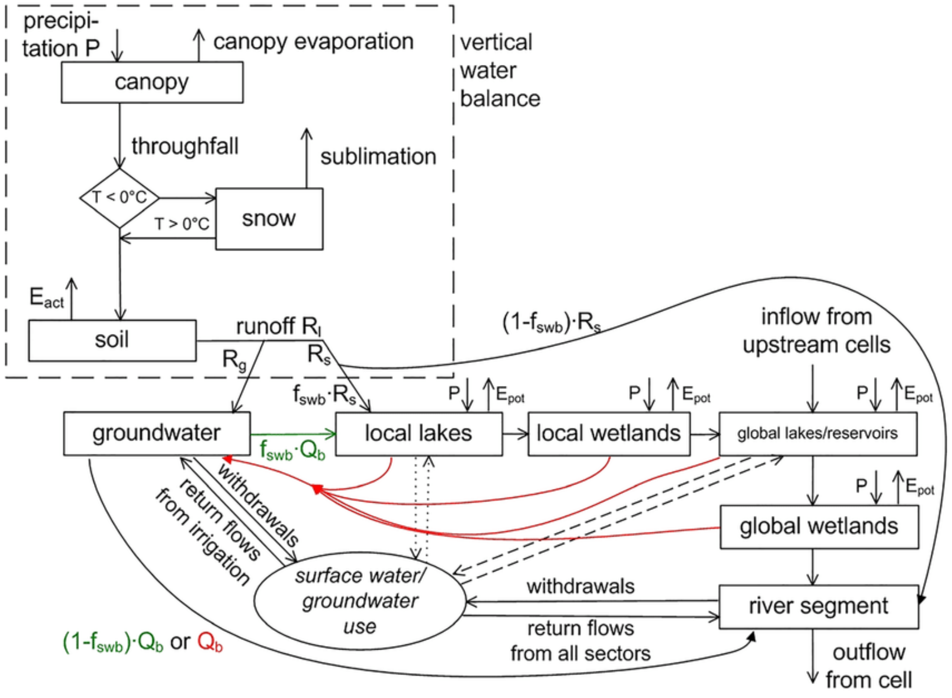


Figure 21: Schematic overview of the WaterGAP model

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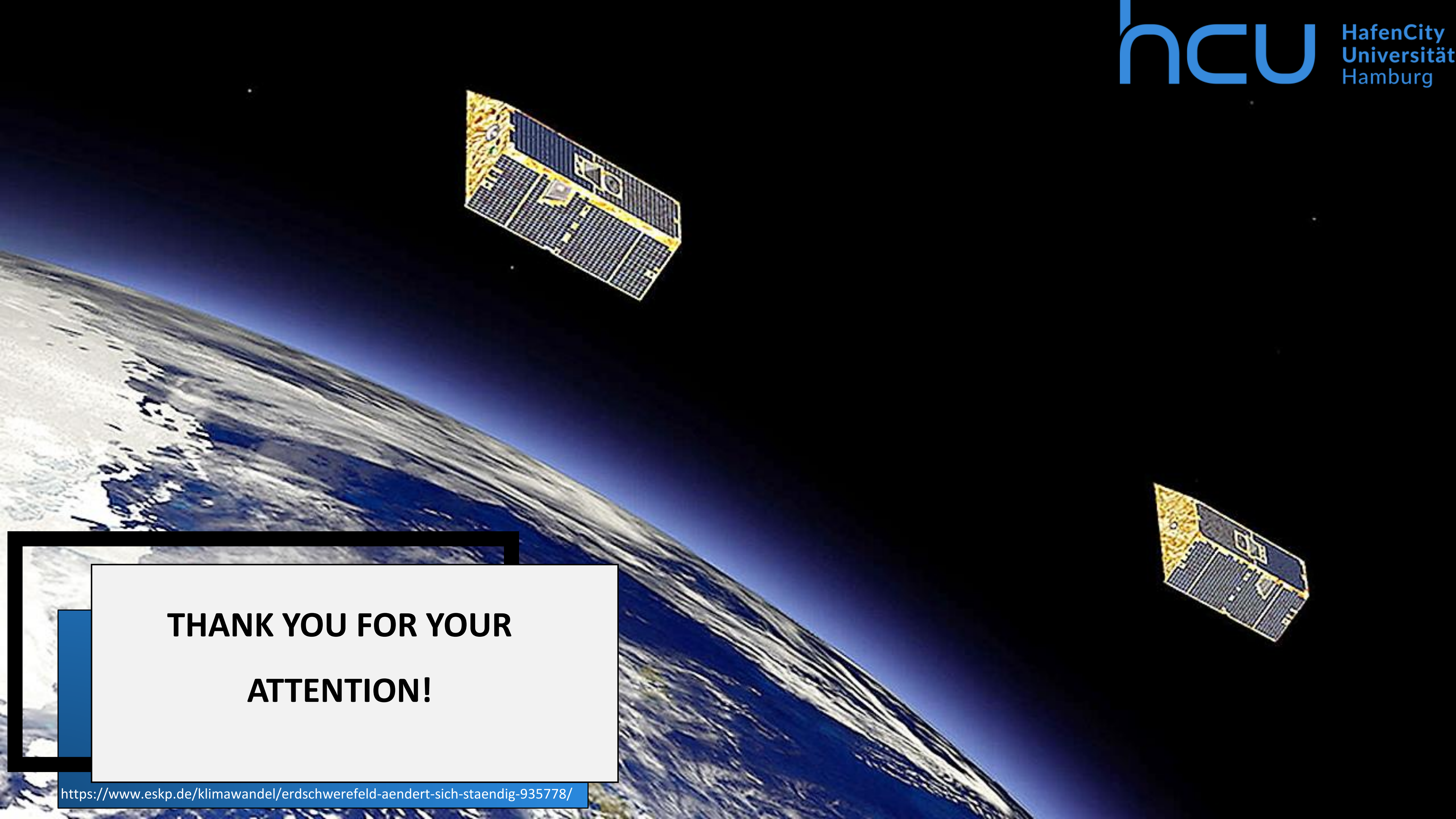


THANK YOU FOR YOUR ATTENTION!

https://www.eskp.de/klimawandel/erdschwerefeld-aendert-sich-staendig-935778/

Results - All water bodies

- no direct linear relationship
- slight tendency (?)

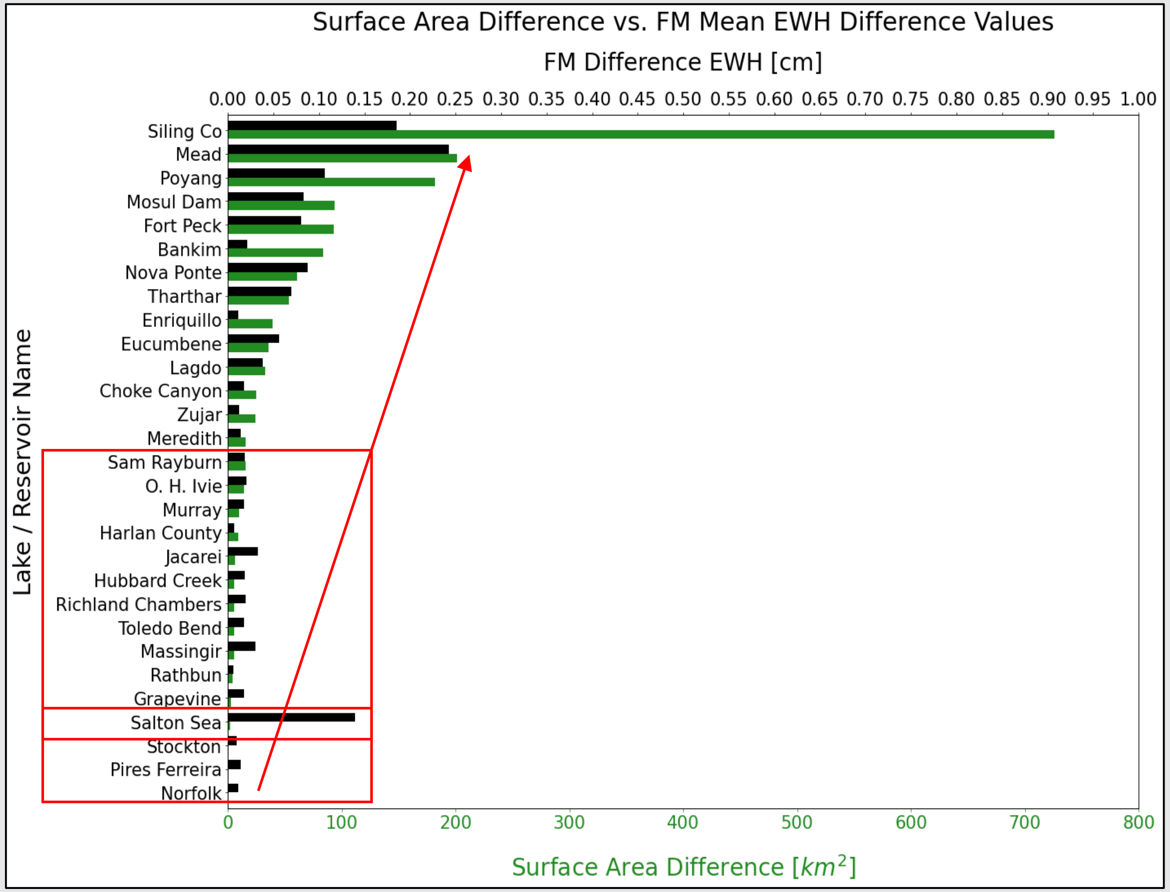


Figure 22: Relation between the surface area difference and the forward modelled mean EWH difference

Results - All water bodies

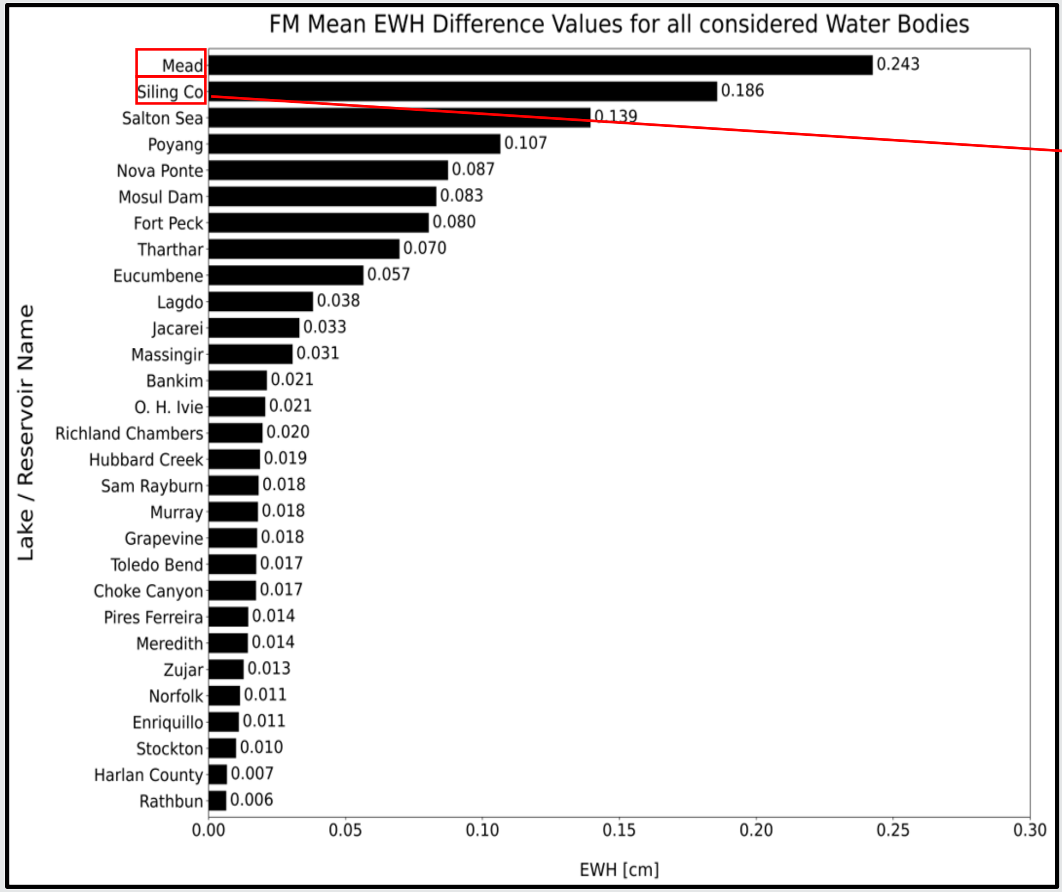


Figure 23: FM Mean EWH Difference values for all considered water bodies

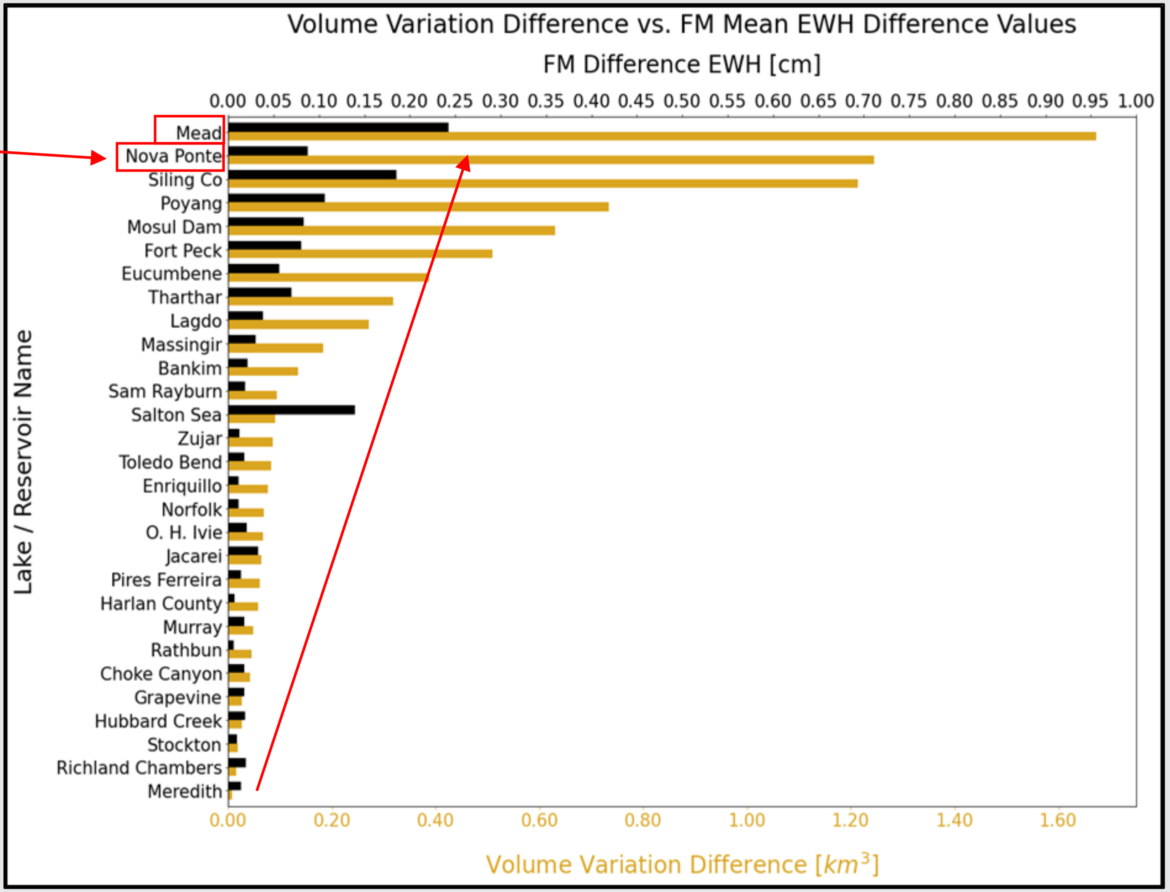


Figure 24: Relation between the surface area difference and the forward modelled mean EWH difference

Results - All water bodies

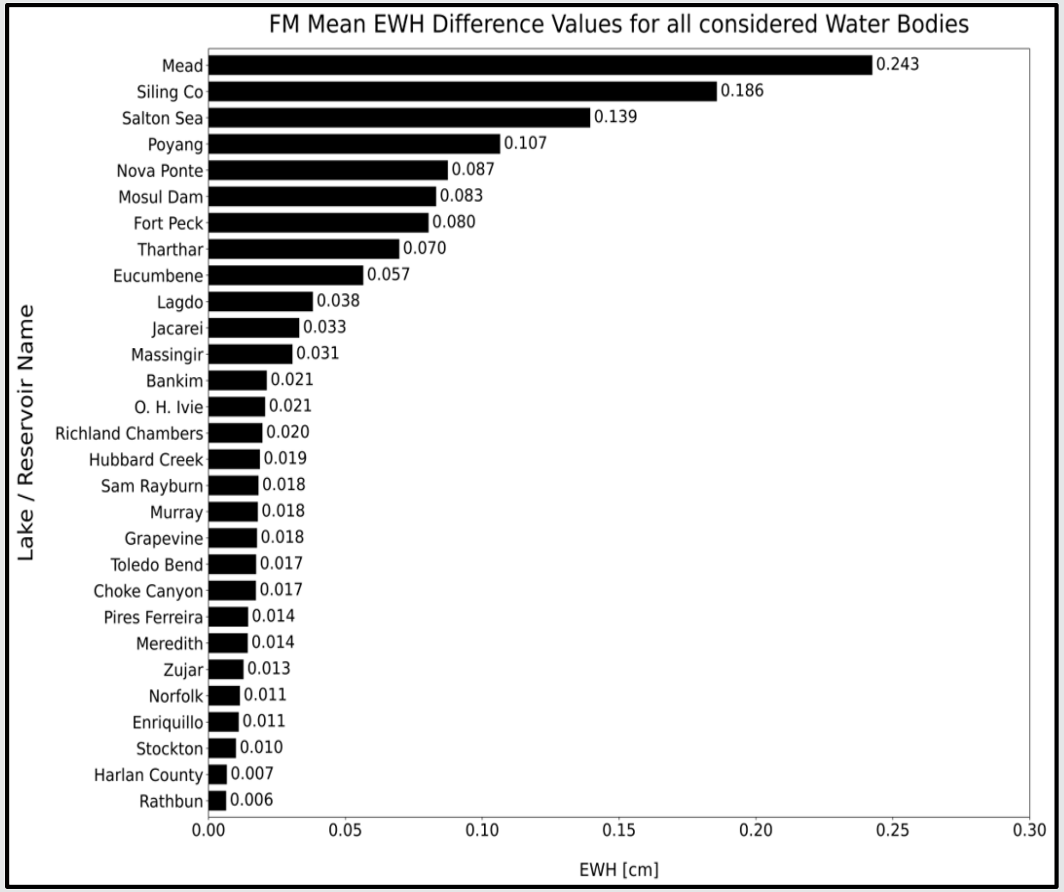


Figure 25: FM Mean EWH Difference values for all considered water bodies

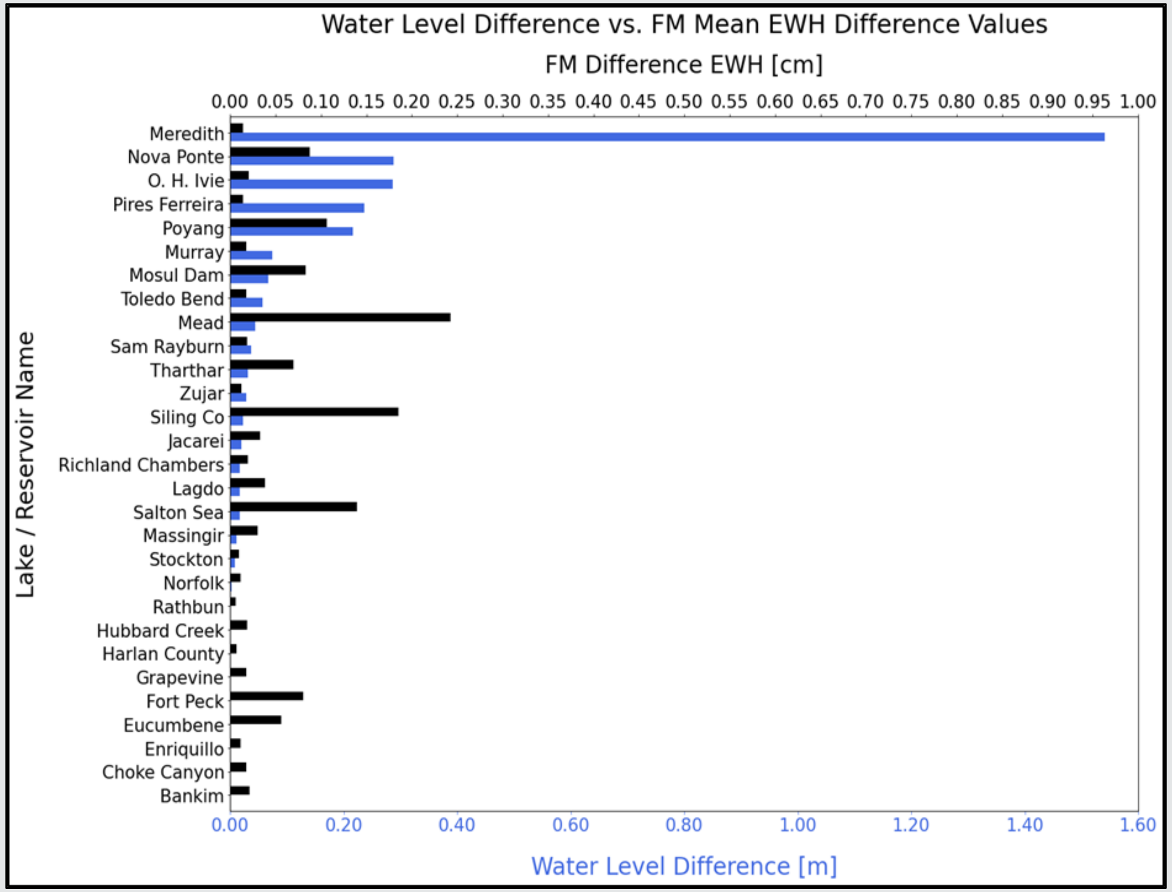


Figure 26: Relation between the water level difference and the forward modelled mean EWH difference

Spherical harmonic potential coefficients

- Gravity field = vector field
- To detect sources of the gravitational force, the Laplace Operator can be used
- Laplace Equation = 0

  -> no mass element

  -> valid for the exterior

  -> Every function which fulfills Laplace equation is called harmonic function. They can be expressed in terms of spherical harmonics e.g. spherical harmonic basis function (describes the potential)

```
product_type            gravity_field
modelname               ITG-Grace03
comment                 static field from 2002-08 to 2007-04 of GRACE data
earth_gravity_constant 3.986004415e+14
radius                  6378136.6
max_degree              180
key n m        C                    S                   sigma C             sigma S
end_of_head ========================================================================
gfc 0 0  1.000000000000e+00  0.000000000000e+00 0.000000000000e+00 0.000000000000e+00
gfc 1 0  0.000000000000e+00  0.000000000000e+00 0.000000000000e+00 0.000000000000e+00
gfc 1 1  0.000000000000e+00  0.000000000000e+00 0.000000000000e+00 0.000000000000e+00
gfc 2 0 -4.841692718699e-04  0.000000000000e+00 6.469883774458e-13 0.000000000000e+00
gfc 2 1 -2.654790999243e-10  1.475393314283e-09 6.108979511966e-13 6.355307212507e-13
gfc 2 2  2.439383367978e-06 -1.400273635220e-06 6.254221806143e-13 6.423410956098e-13
gfc 3 0  9.571610348416e-07  0.000000000000e+00 4.908157850872e-13 0.000000000000e+00
gfc 3 1  2.030461736678e-06  2.482003394707e-07 4.904543816334e-13 5.118675157415e-13
gfc 3 2  9.047877724984e-07 -6.190053685183e-07 5.459595906001e-13 5.482674767117e-13
gfc 3 3  7.213217237276e-07  1.414349090196e-06 5.163836126113e-13 5.163483433061e-13
gfc 4 0  5.399657665980e-07  0.000000000000e+00 3.758481731782e-13 0.000000000000e+00
gfc 4 1 -5.361573220519e-07 -4.735672404588e-07 3.874699557956e-13 3.973550735355e-13
gfc 4 2  3.505015650151e-07  6.624798955603e-07 4.501829959710e-13 4.398486563277e-13
gfc 4 3  9.908565738322e-07 -2.009566568843e-07 4.776067657084e-13 4.766590461153e-13
gfc 4 4 -1.885196275153e-07  3.088038091544e-07 4.556511148108e-13 4.565287154679e-13
gfc 5 0  6.867029195170e-08  0.000000000000e+00 2.444626602968e-13 0.000000000000e+00
gfc 5 1 -6.292117216708e-08 -9.436975416042e-08 2.510438328896e-13 2.640391465060e-13
-...
```

Figure 27: Spherical harmonic coefficients for a specific month

Legendre Functions

- To detect sources of the gravitational force, the Laplace Operator can be used
- Laplace Equation = 0

  -> no mass element
- Solution for the Laplace Equation can be separated into two parts

  -> one part depends on the longitude (changes along a circle of latitude; expressed by sin + cos terms)

  -> one part depends on co-latitude (changes along a meridian; known as Legendre Function)

$$V(\lambda, \vartheta, r) = \sum_{n=0}^{\infty} \frac{1}{r^{n+1}} \sum_{m=0}^{n} c_{nm} P_n^m(\cos\vartheta) \cos(m\lambda) + s_{nm} P_n^m(\cos\vartheta) \sin(m\lambda)$$

$$p(\vartheta) = P_n^m(\cos\vartheta)$$

Co-Latitude

Equation 3: Spherical Harmonic Expansion of the Potential & Legrendre Function

Degree and Order

- The higher the maximum degree n, the more detail structures can be represented

$$f(\lambda,\vartheta) = \sum_{n=0}^{\infty}\sum_{m=0}^{n} c_{nm}\, P_n^m(\cos\vartheta)\cos(m\lambda) + s_{nm} P_n^m(\cos\vartheta)\sin(m\lambda)$$

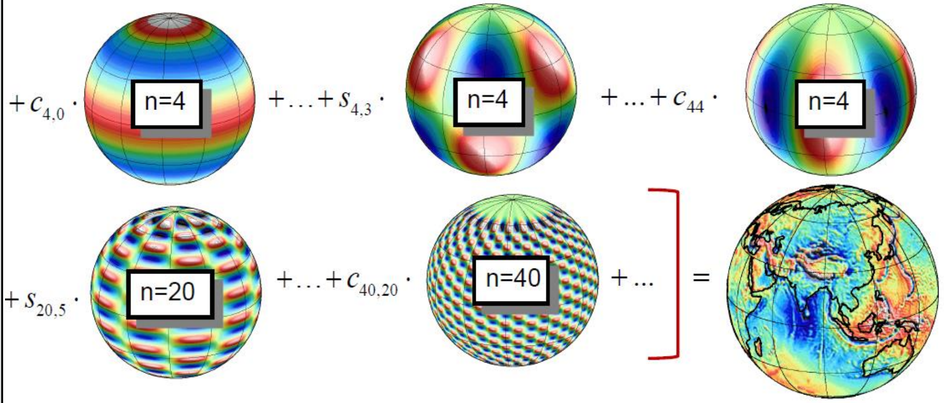


Figure 28: Spherical Harmonic Synthesis

Load Love Numbers

- The Earth reacts viscoelastic to loading masses

  -> viscous material (like honey) expands linearly with time when a stress is applied -> long time scales -> GIA
  -> elastic material (like a rubber band) deforms directly and quickly returns to it‘s original state once the stress is removed -> short time scales < 100 years

- Elastic deformation theory was developed in 1911 by Augustus Edward Hough Love.

  Load Love numbers describe the elastic reaction of the Earth’s mantle and crust to the loading mass at the surface.

  Integrating them into the spherical harmonic expansion allows to separate surface load changes from mass loss in the mantle -> determine mass changes of the surface load.

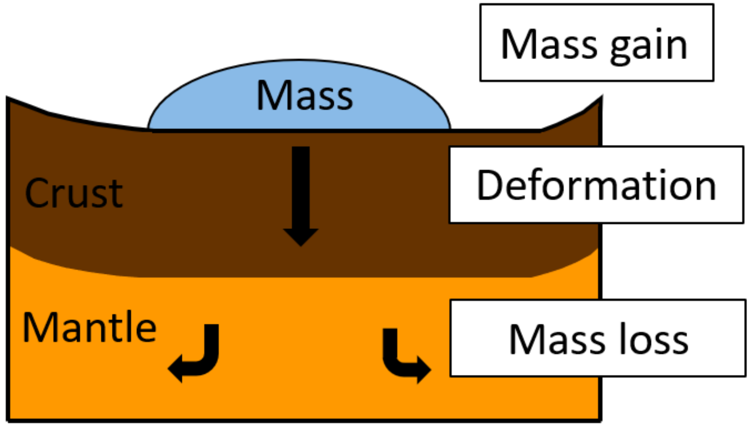


Figure 29: Loading

Equivalent Water Height

- GRACE observes the gravitational potential (spherical harmonics)
- A change in the potential can be converted to mass change, which is expressed in terms of EWH
- EWH allows to express changes of the gravity field in hydrological units

  -> EWH refers to the thickness of a uniform layer of water which is equivalent to the observed mass change

  -> it depends on the mass

  -> deeper pixel column = higher mass = more EWH

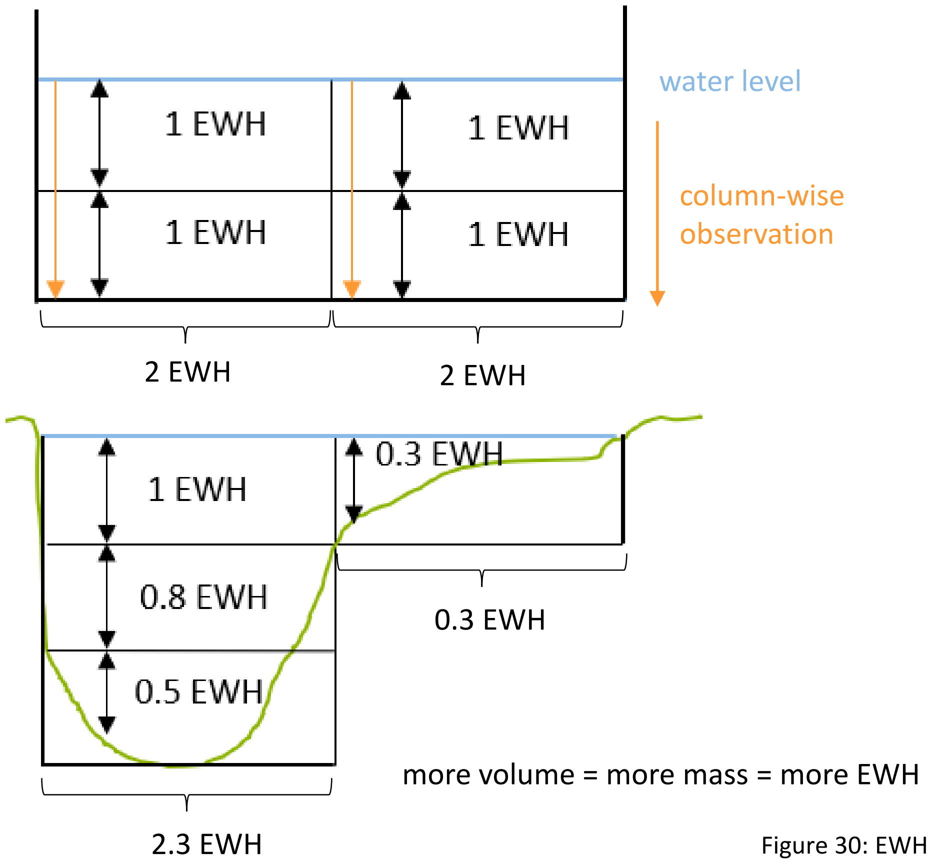


Figure 30: EWH

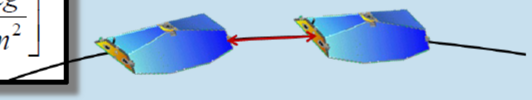
Equivalent Water Height

Surface density => equivalent water heights

HCU HafenCity Universität Hamburg

Surface density from gravitational potential

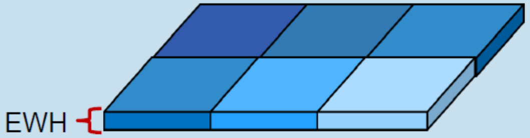
$$\mu(\lambda,\vartheta)=\frac{M}{4\pi R^2}\sum_{n=0}^{\infty}(2n+1)\sum_{m=-n}^{n}a_{nm}Y_{nm}(\lambda,\vartheta)\quad\left[\frac{kg}{m^2}\right]$$



Equivalent water height

$$EWH(\lambda,\vartheta)=\frac{\mu(\lambda,\vartheta)}{\rho_w}[m]=\left[\frac{kg}{m^2}\right]\Big/\left[\frac{kg}{m^3}\right]$$

ρ_w : density of water



Equivalent water heights (EWH)

$$EWH(\lambda,\vartheta)=\frac{M}{\rho_w 4\pi R^2}\sum_{n=0}^{\infty}(2n+1)\sum_{m=-n}^{n}a_{nm}Y_{nm}(\lambda,\vartheta)\quad[m]$$

= thickness of a uniform layer of water which is equivalent to the observed mass change

Take home message (1)

GRACE observes the gravitational potential (spherical harmonics).

Change in potential can easily be converted to mass change, generally expressed in terms of equivalent water heights (EWH).

Results - Linear Trend

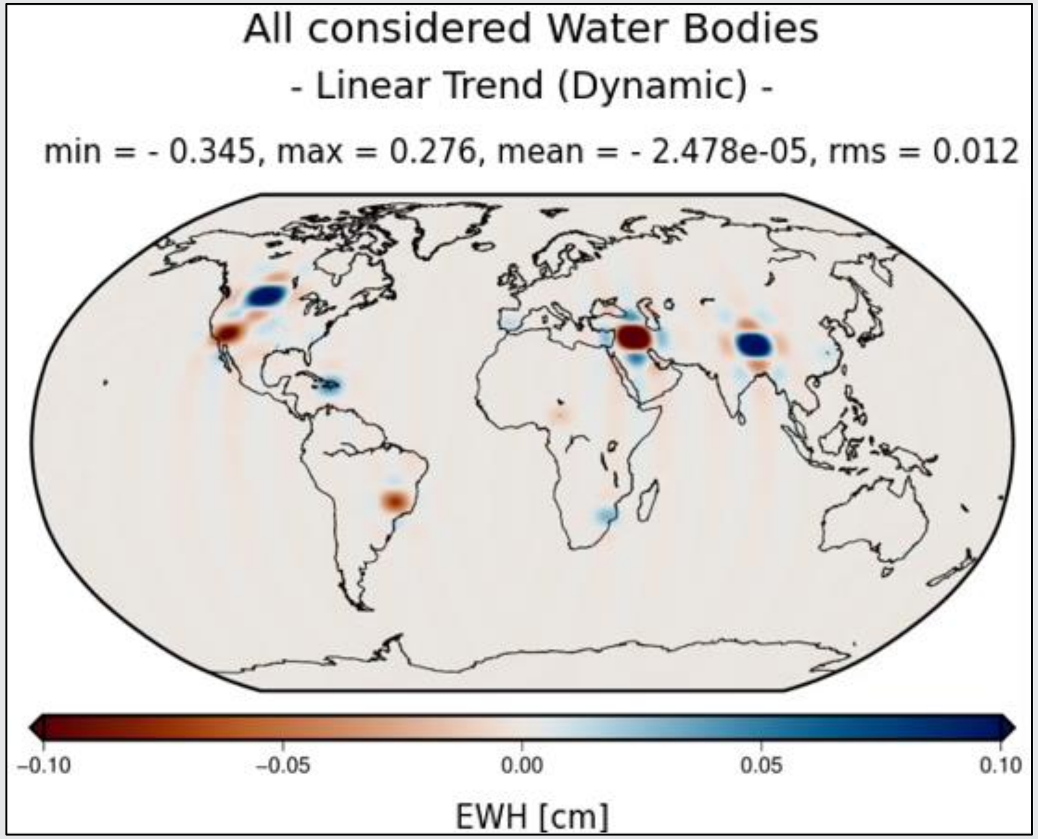


Figure 31: Linear Trend (Dynamic) for all considered water bodies

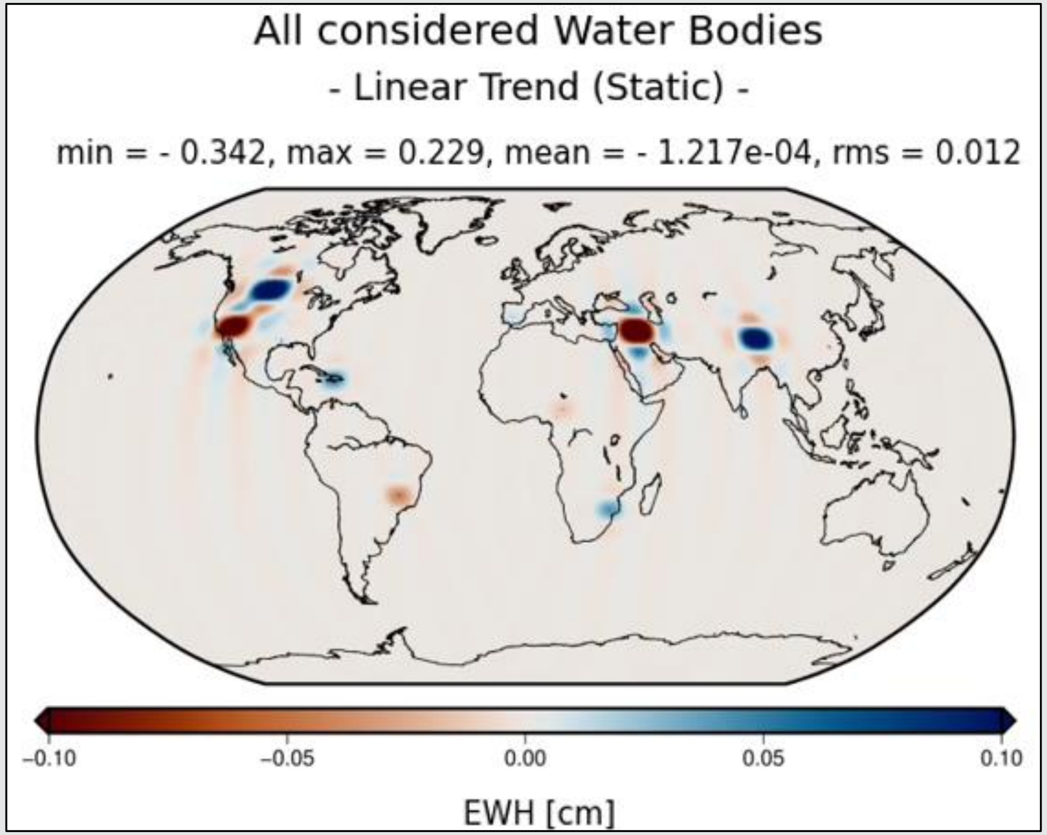


Figure 32: Linear Trend (Static) for all considered water bodies

Results - Amplitude

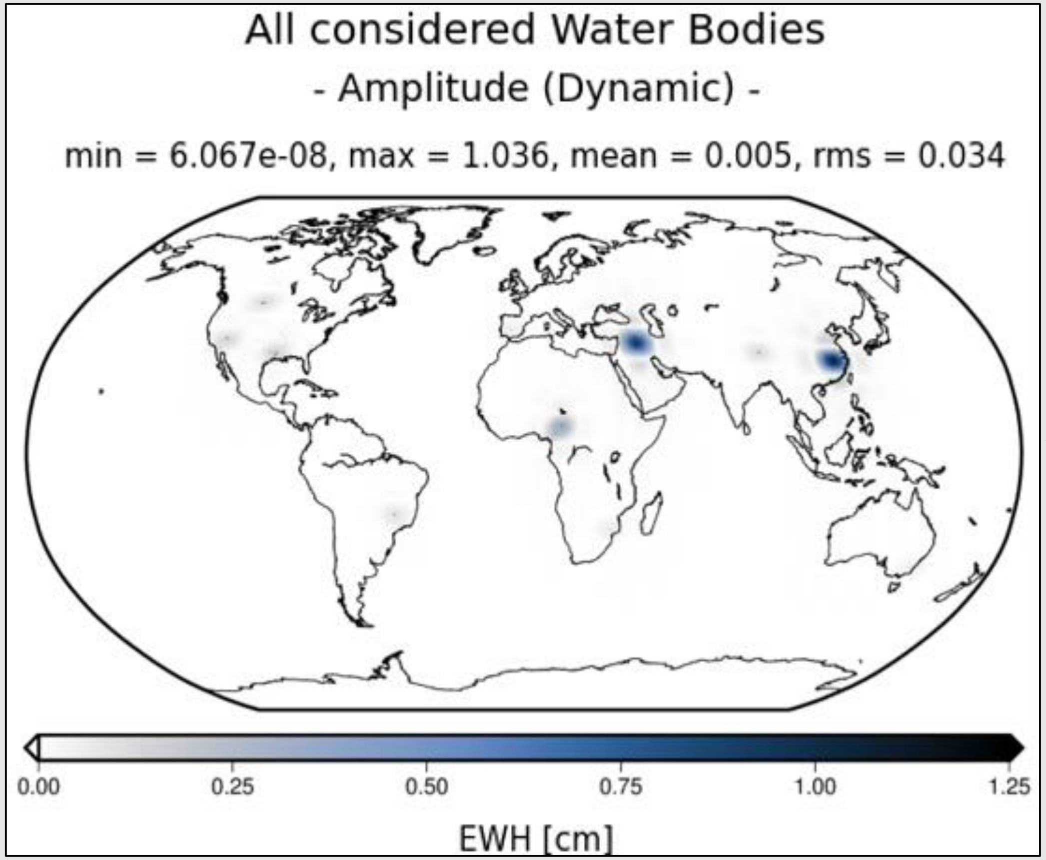


Figure 33: Amplitude (Dynamic) for all considered water bodies

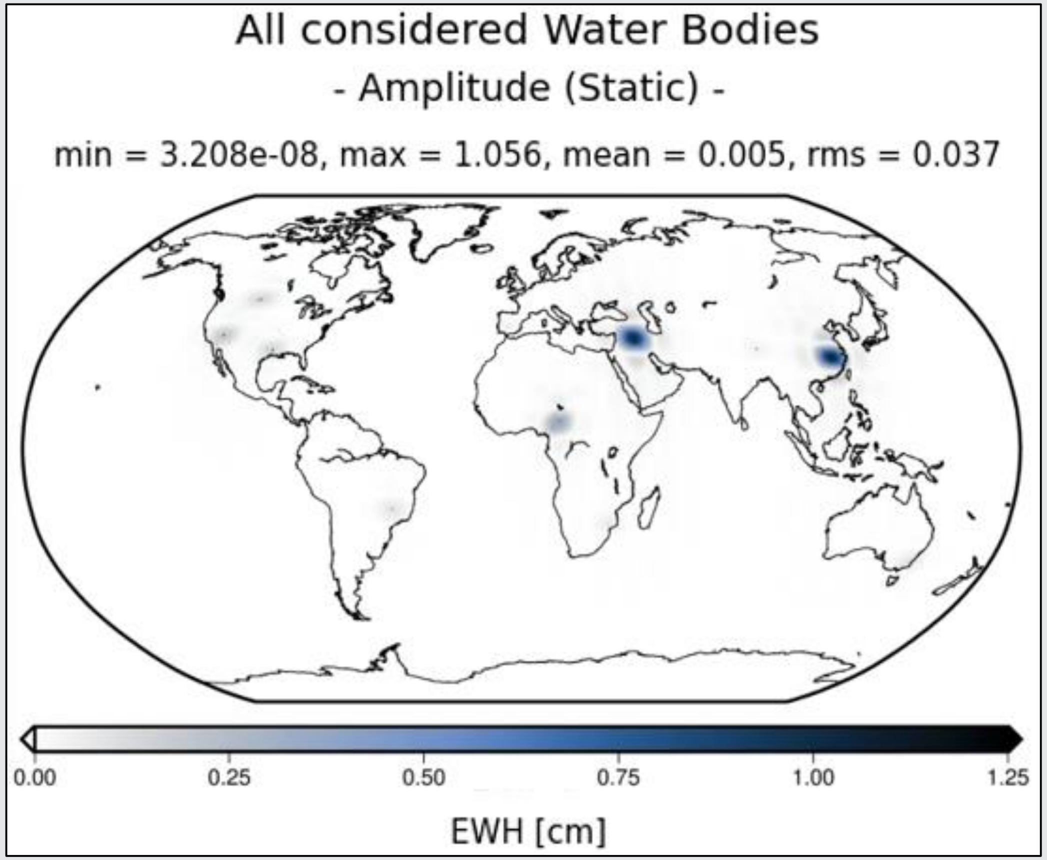


Figure 34: Amplitude (Static) for all considered water bodies