Estimation of Groundwater Storage: Can Storage Change Derived from the Gravity Recovery & Climate Experiment (GRACE) be a Substitute for a Calibrated Numerical Flow Model?

Elif Aysu BATKAN[1], M. Berker BAYIRTEPE[1], Barış ÇAYLAK[1], A. Hakan ÖREN[2], Alper ELÇİ[3]

[1] Graduate School of Natural and Applied Sciences, Dokuz Eylül University, Izmir, Turkiye
[2] Department of Civil Engineering, Dokuz Eylül University, Izmir, Turkiye
[3] Department of Environmental Engineering, Dokuz Eylül University, Izmir, Turkiye

Problem Statement

- ❑ In many parts of the world, information about the availability of groundwater and the change in storage is limited mainly due to the lack of periodical quantitative monitoring and the reluctance to data sharing. Therefore, the estimation of groundwater storage is challenging.
- ❑ Groundwater flow models require miscellaneous input data for their setup and execution, but more importantly, they must be calibrated with the aim to obtain solutions that are sufficiently close to filed observations.
- ❑ The calibration of a groundwater flow model requires observation data, for example groundwater level measurements at numerous locations in the study area. These measurement devices are usually in the form of observation wells, which are usually screened in aquifers.
- ❑ The problem often is that these observation data can be scarce and even if available, difficult to access due to unwillingness of public institutions to share the data.

Research Question

Can **groundwater storage change** derived from the **GRACE mission data** be a substitute for storage change estimates obtained from a calibrated numerical flow model?

Objectives

I. To present a **comparative analysis** of two approaches that can be used in groundwater storage estimation.

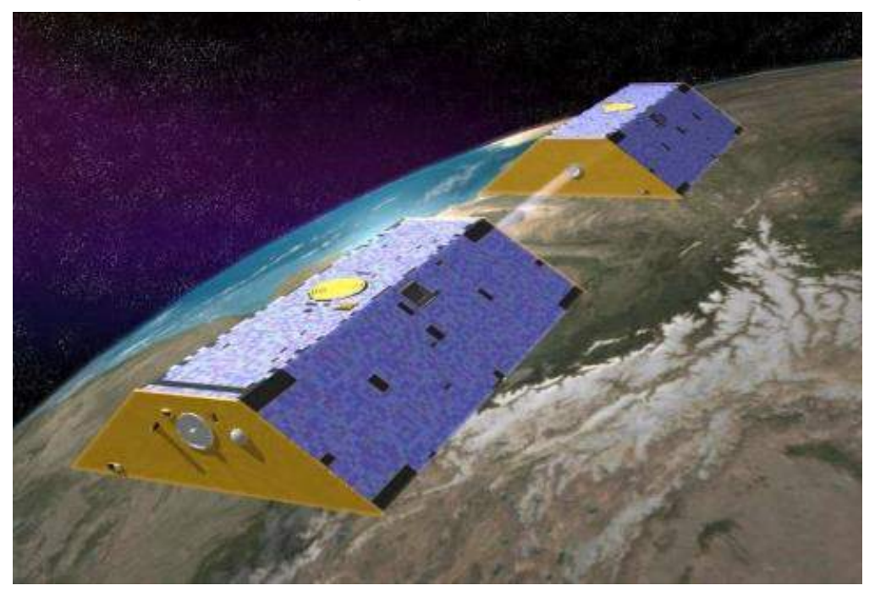
II. To **develop a new approach** for characterization and mathematical simulation of the water storage capacity of large aquifer systems using low cost and non-intrusive data with satellite-based EO techniques for sustainable water management.

III. Investigate feasibility to replace conventional observation data (e.g. hydraulic head measurements) and reduce model parameter uncertainties in **utilizing groundwater storage as a model calibration parameter**.

The GRACE & GRACE-FO Missions

The **G**ravity **R**ecovery **and** **C**limate **E**xperiment (GRACE) is a joined mission of NASA and German Aerospace Center (DLR) to accurately map variations in Earth's gravity field.

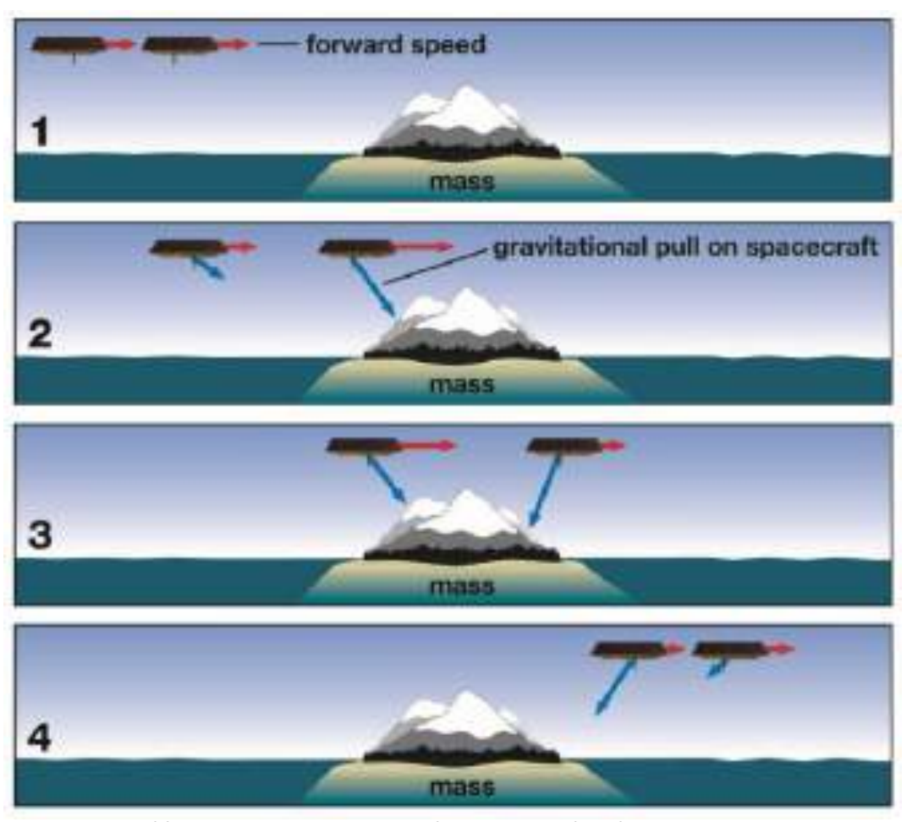
- ❑GRACE: March 17, 2002 to October 12, 2017
- ❑GRACE Follow-On: May 18, 2018 to present
- ❑Twin-satellite
- ❑Sun-synchronous orbit
- ❑220 km apart at an altitude of 500 km



https://grace.jpl.nasa.gov/news/116/jpls-grace-mission-at-20-years/

Measurements from GRACE & GRACE-FO Missions

- ❑ GRACE satellites detect small changes in the Earth's gravity field caused primarily by **water movements on or beneath the land surface**.
- ❑ Fundamental of physics are used to translate GRACE measurements to **gravity** or **mass concentration**.
- ❑ Variations in gravity observed by GRACE are interoperated as **terrestrial water storage (TWS) changes,** provided in cm of equivalent water thickness.

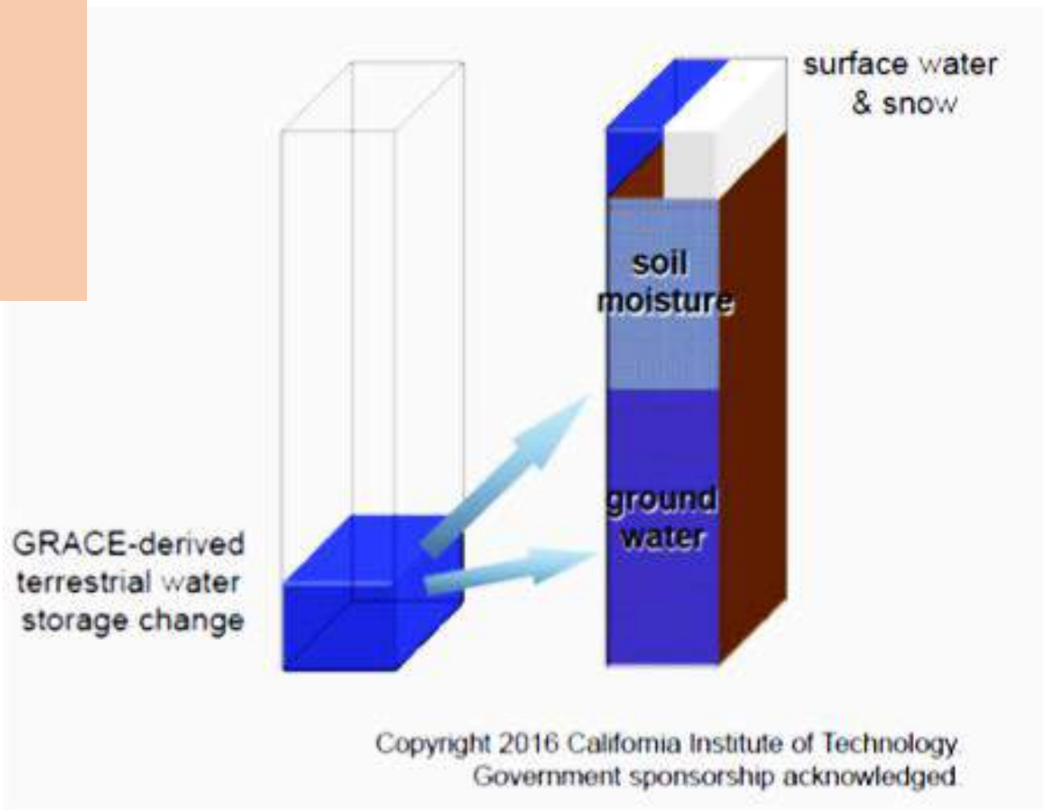


https://gracefo.jpl.nasa.gov/resources/50/how-grace-fo-measures-gravity/

From Terrestrial Water to Groundwater

$$P - ET - Q = \Delta \mathrm{TWS}$$
$$\Delta TWS = \Delta \mathrm{GW} + \Delta \mathrm{SM} + \Delta \mathrm{SWE} + \Delta \mathrm{SW}$$
$$\Delta GW = \Delta \mathrm{TWS} - \Delta \mathrm{SM} - \cancel{\Delta \mathrm{SWE}} - \cancel{\Delta \mathrm{SW}}$$
$$\boxed{\Delta GW = \Delta \mathrm{TWS} - \Delta \mathrm{SM}}$$

P: Precipitation
ET: Evapotranspiration
Q: Surface water flow
ΔTWS: Change in terrestrial water storage
ΔGW: Change in groundwater storage
ΔSWE: Change in snow water equivalent
ΔSW: Change in surface water storage
ΔSM: Change in soil moisture



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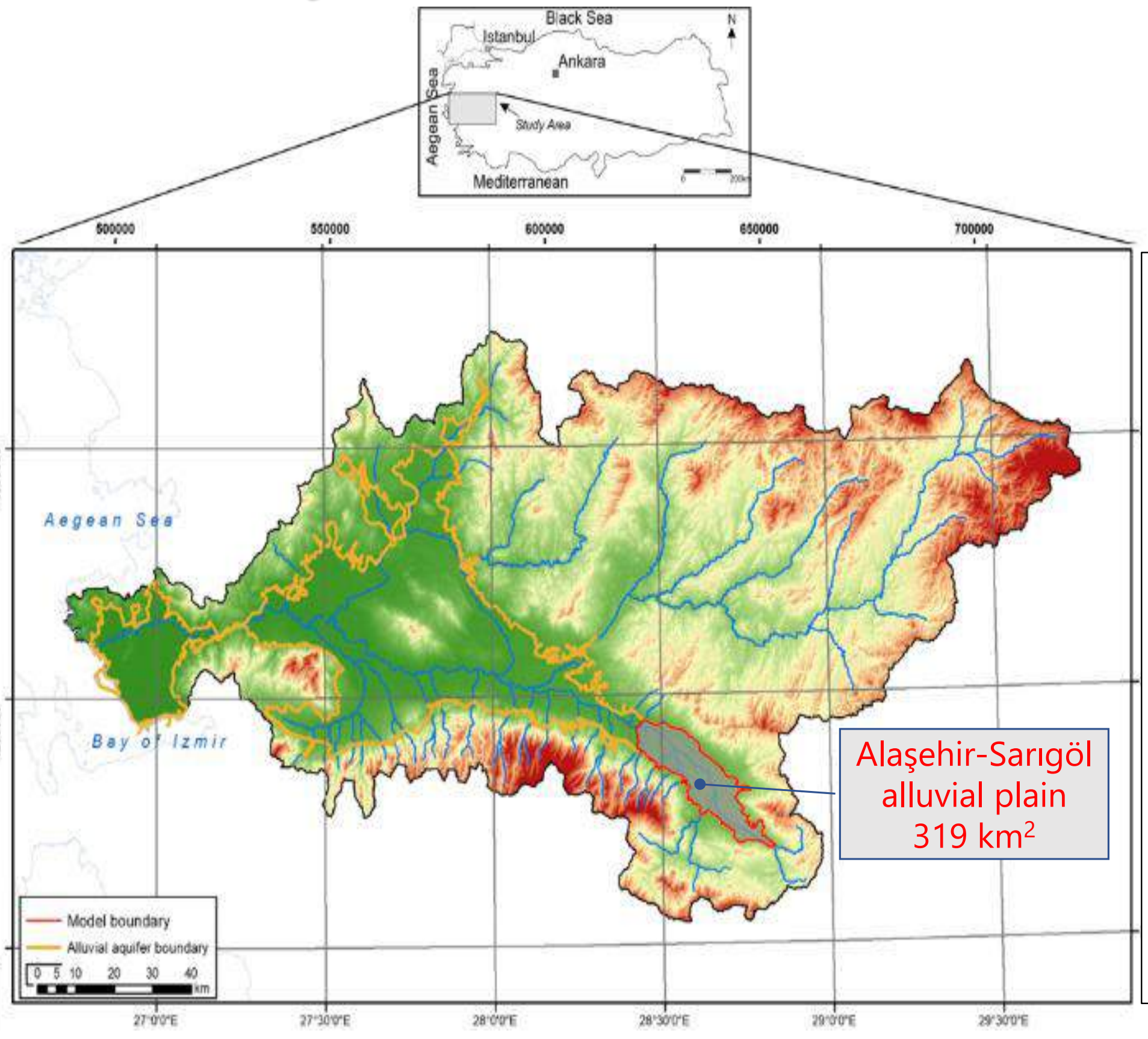
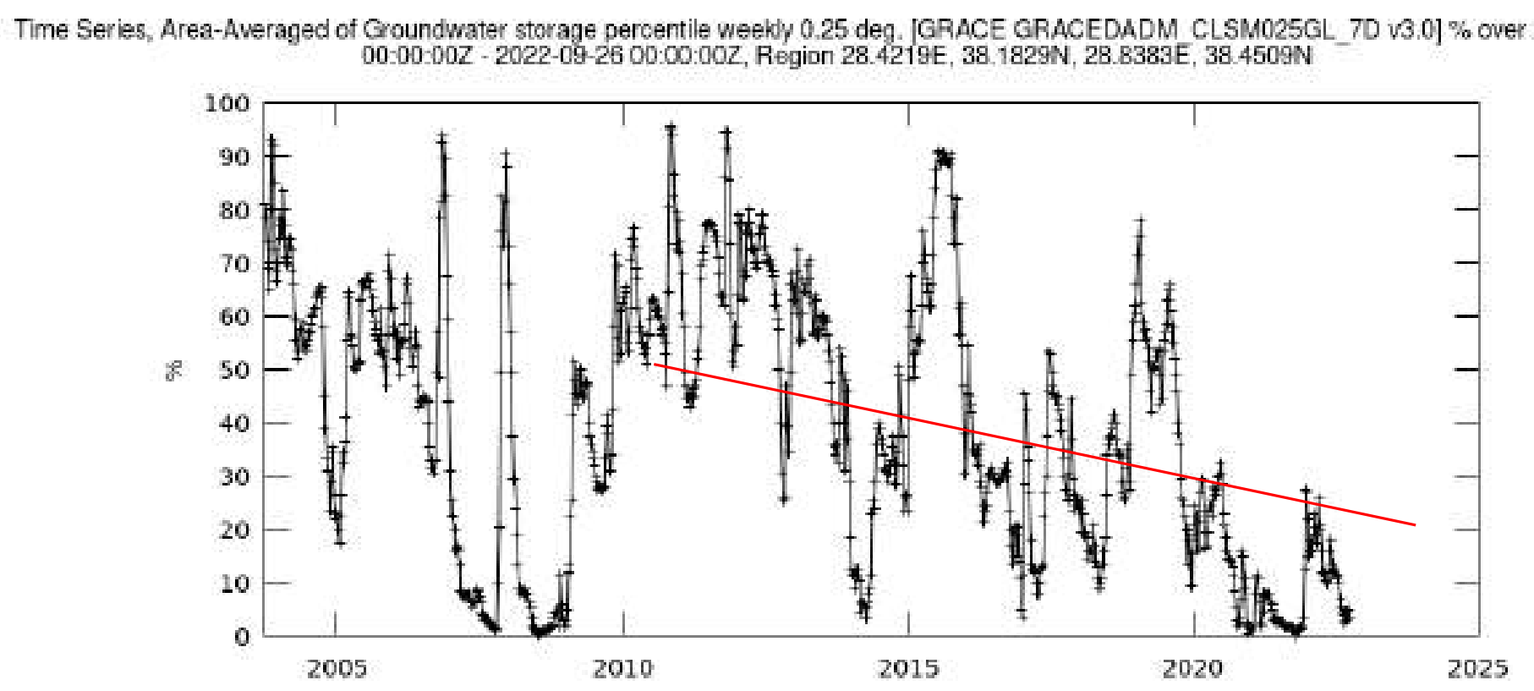
One Example of GRACE Data Assimilation of in Hydrological Models

- ❑ GLDAS Version 2.2 **assimilates GRACE TWS data** and can provide all the water budget components, including groundwater, at a higher resolution.
- ❑ Validation of **groundwater storage** from GLDAS version 2.2 (→ GRACE data amended) with well measurements suggests that GRACE data assimilation improves groundwater storage estimation by 36% at the regional scale and by 10% at the point scale (Li et al., 2019).

Study Area: Gediz River Basin (GRB)



- Drainage area = 17,146 km^2. Gediz River Basin (GRB) is one of the largest out of 25 major river basins in Turkiye.
- One of the most water-stressed river basins in Turkiye.
- Mean precipitation = 526 mm/a
- The alluvial aquifer in the basin has the most groundwater potential and provides irrigation water for crop production.
- The GRB is considered as one of the most water-stressed river basins in Turkiye due to over-exploitation of groundwater.



Data available at nasagrace.unl.edu through a partnership with the National Drought Mitigation Center.

Fig. 1: Change in groundwater storage percentile based on the cumulative distribution function of conditions during 1948-2014 simulated by the CLSM models. Decreasing trend in recent 13 years is apparent.

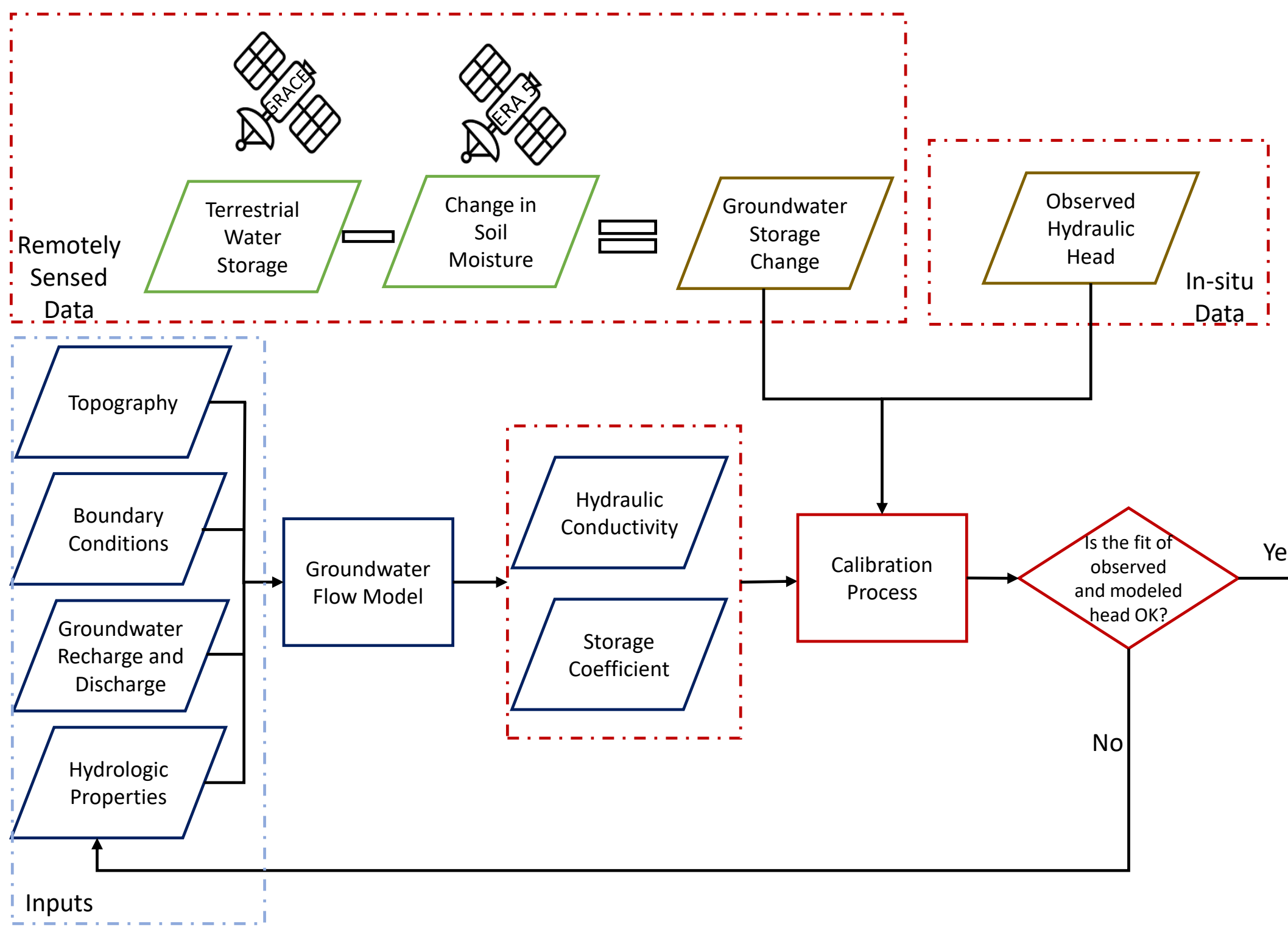


Fig. 2: Proposed groundwater flow modeling process that assimilates gw storage data from GRACE.

Groundwater Flow Model Properties & Input

Groundwater flow in the GRB alluvial aquifer is simulated using the 3D finite-difference groundwater flow model MODFLOW-2005.

The model was constructed with Modelmuse 5.0 (Winston, 2022), an interface of MODFLOW-2005, and various other models developed and maintained by the U.S. Geological Survey.

The governing equation that represents the three-dimensional movement of constant-density groundwater in saturated porous media is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W = S_s\frac{\partial h}{\partial t}$$

Spatial Discretization

- Number of layers = 5
- Number of rows = 188
- Number of columns=242
- Total # of active cells = 73810
- Spatial resolution = 150 x 150 m
- Model domain area = 319 km^2

Temporal Discretization

- Simulation period: Oct 2013 - Dec 2021
- 99 fixed monthly time steps
- In blocks of time called stress periods hydrologic stresses are assumed constant.

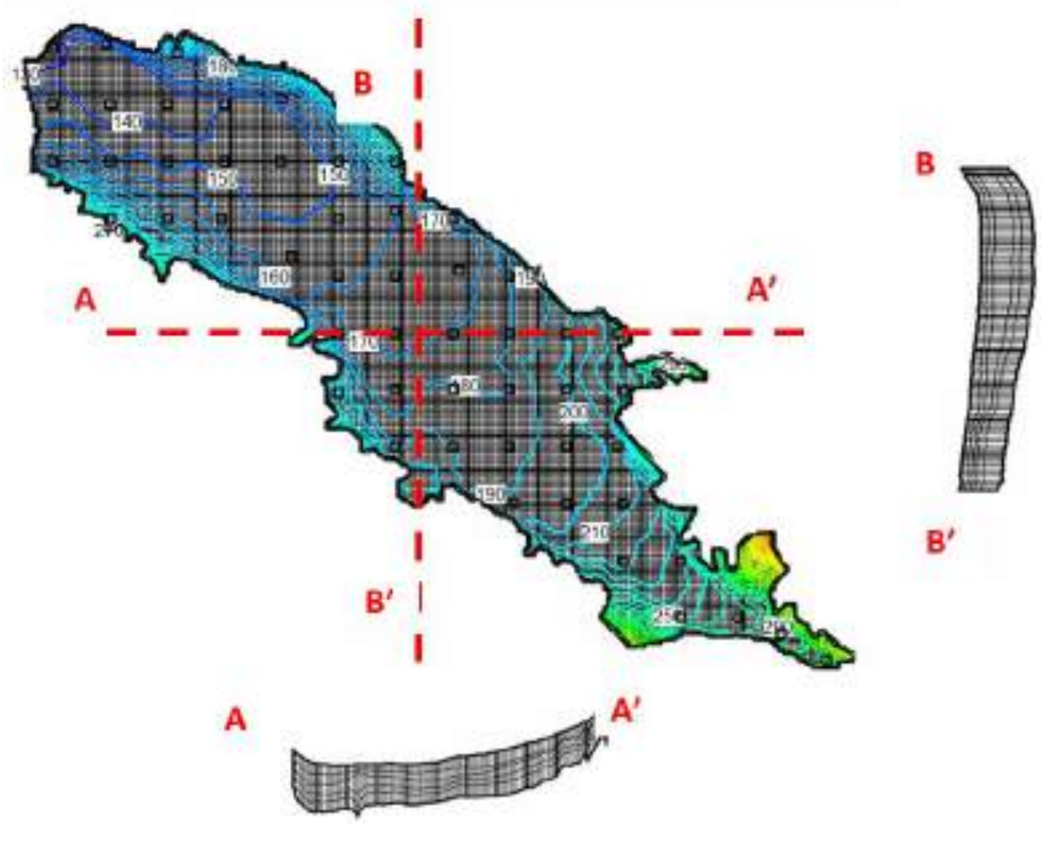


Fig. 3: Plan view and cross-sections of the flow model grid for the GRB alluvial aquifer. Contours represent elevations of the bottom surface of model layer 1.

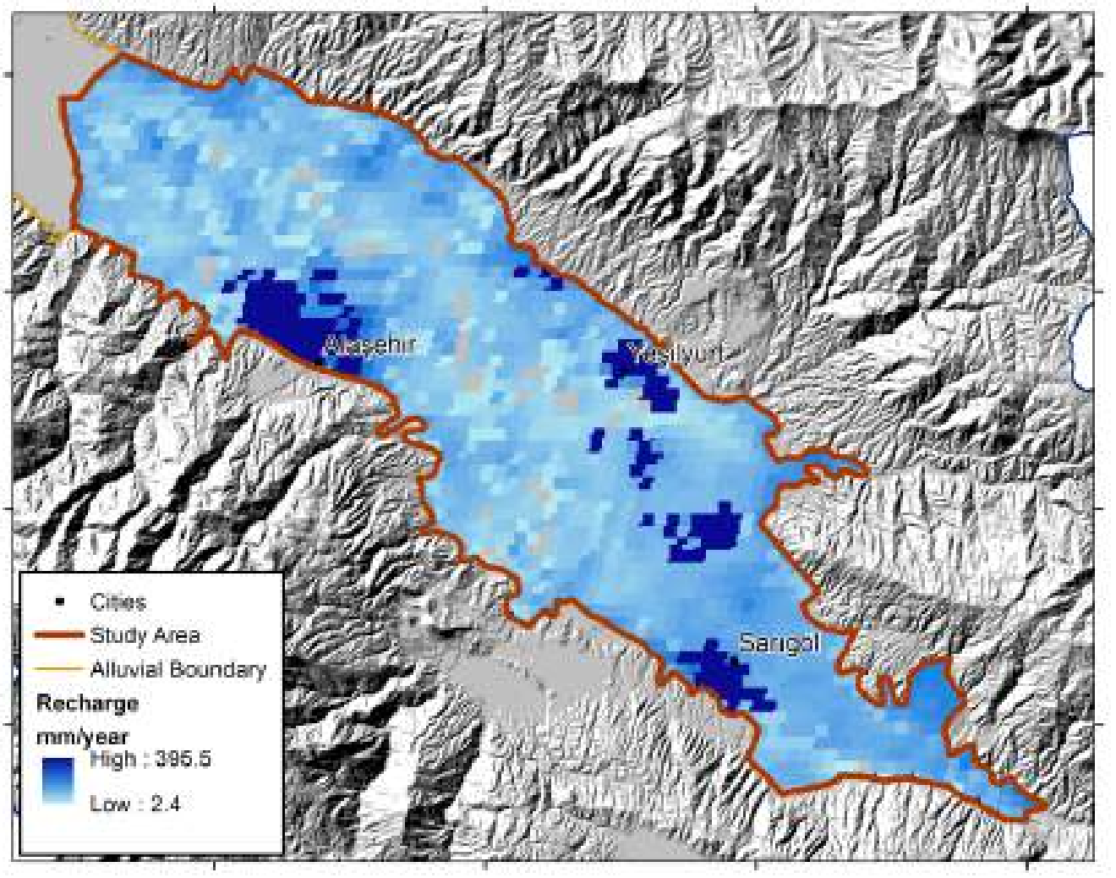
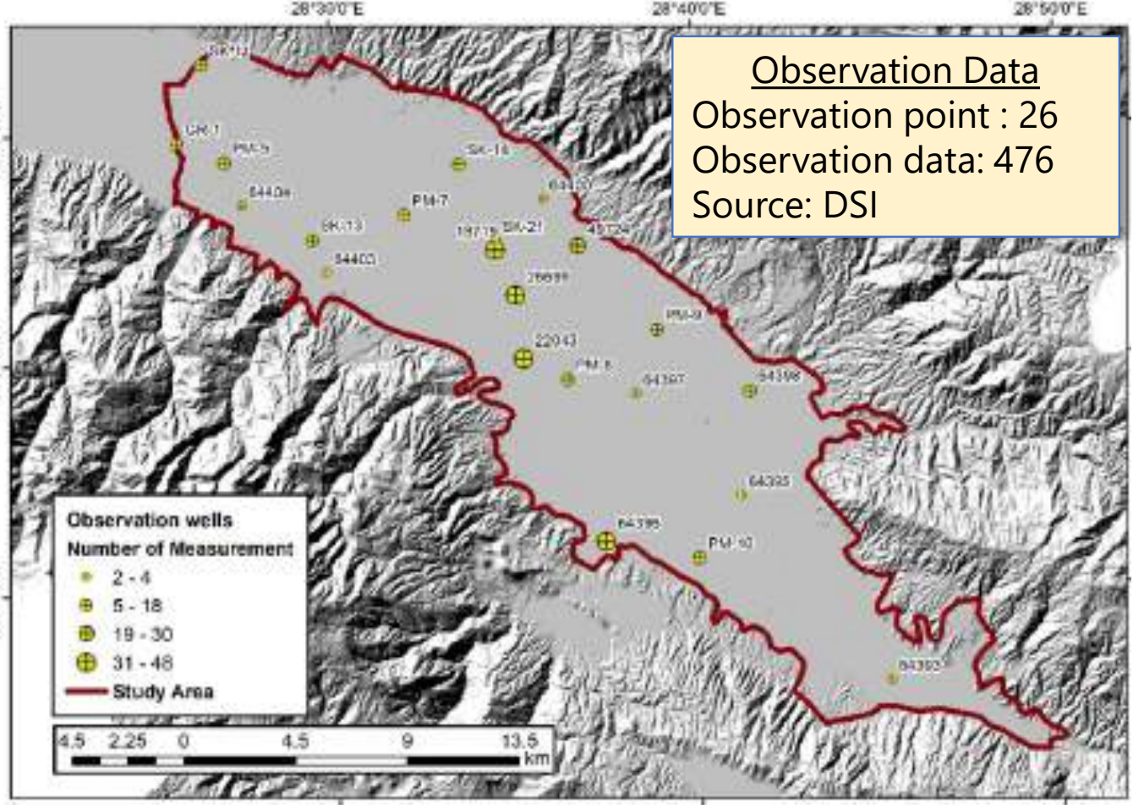
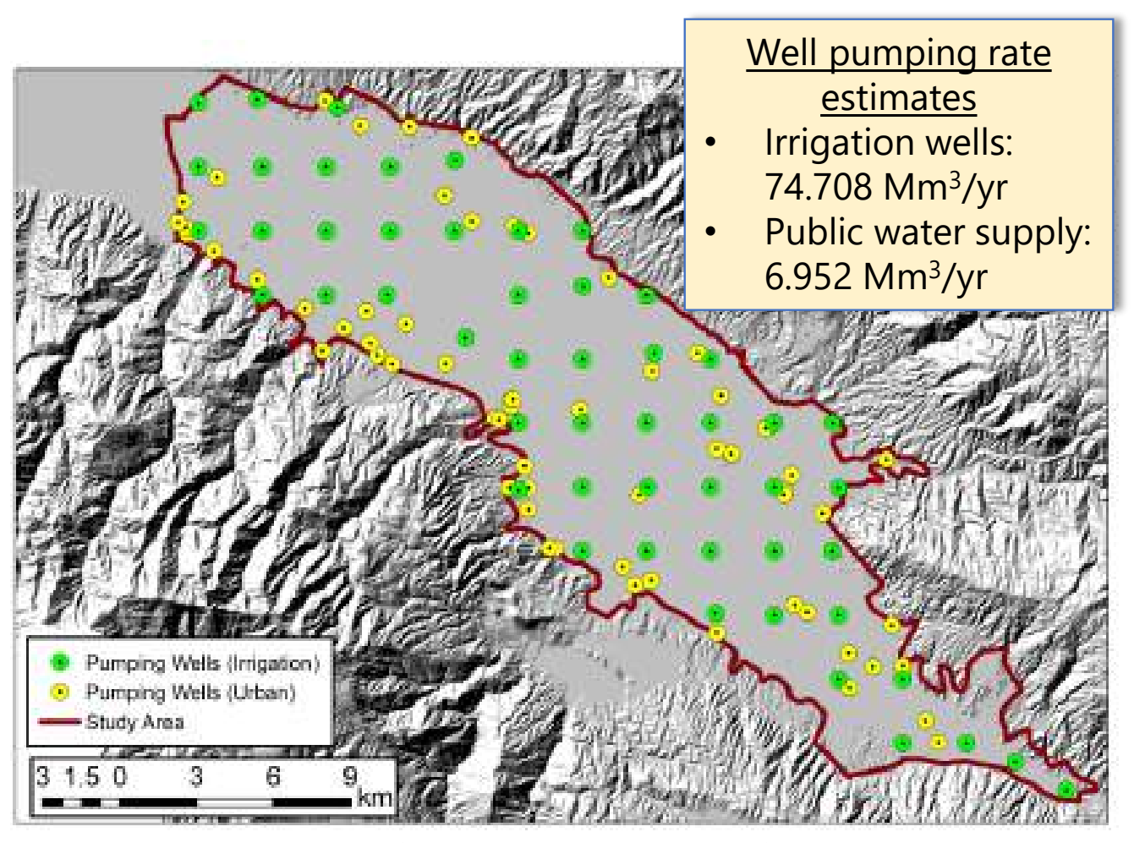


Fig. 4: Mean annual groundwater recharge rate obtained with ERA5-data based water balance method



Observation Data
Observation point : 26
Observation data: 476
Source: DSI

Fig. 5: Groundwater monitoring well locations and calibration data availability.



Well pumping rate estimates

- Irrigation wells: 74.708 Mm^3/yr
- Public water supply: 6.952 Mm^3/yr

Fig. 6: Location of pumping wells defined in the GRB flow model.

Groundwater Flow Model Output

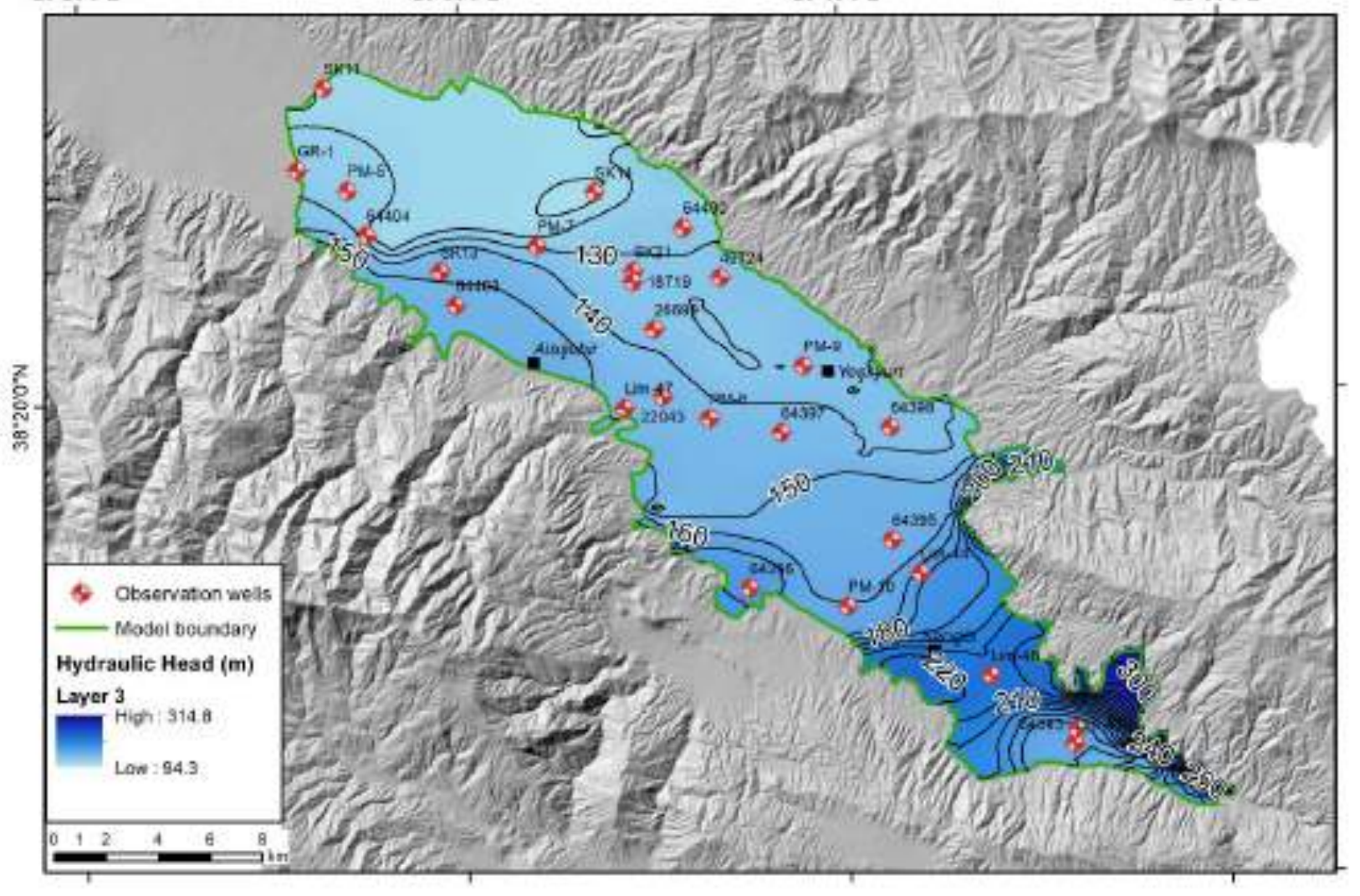


Fig. 7: Simulated hydraulic head in the GRB middle aquifer (Layer 3) at the end of the simulation period (Dec. 2021).

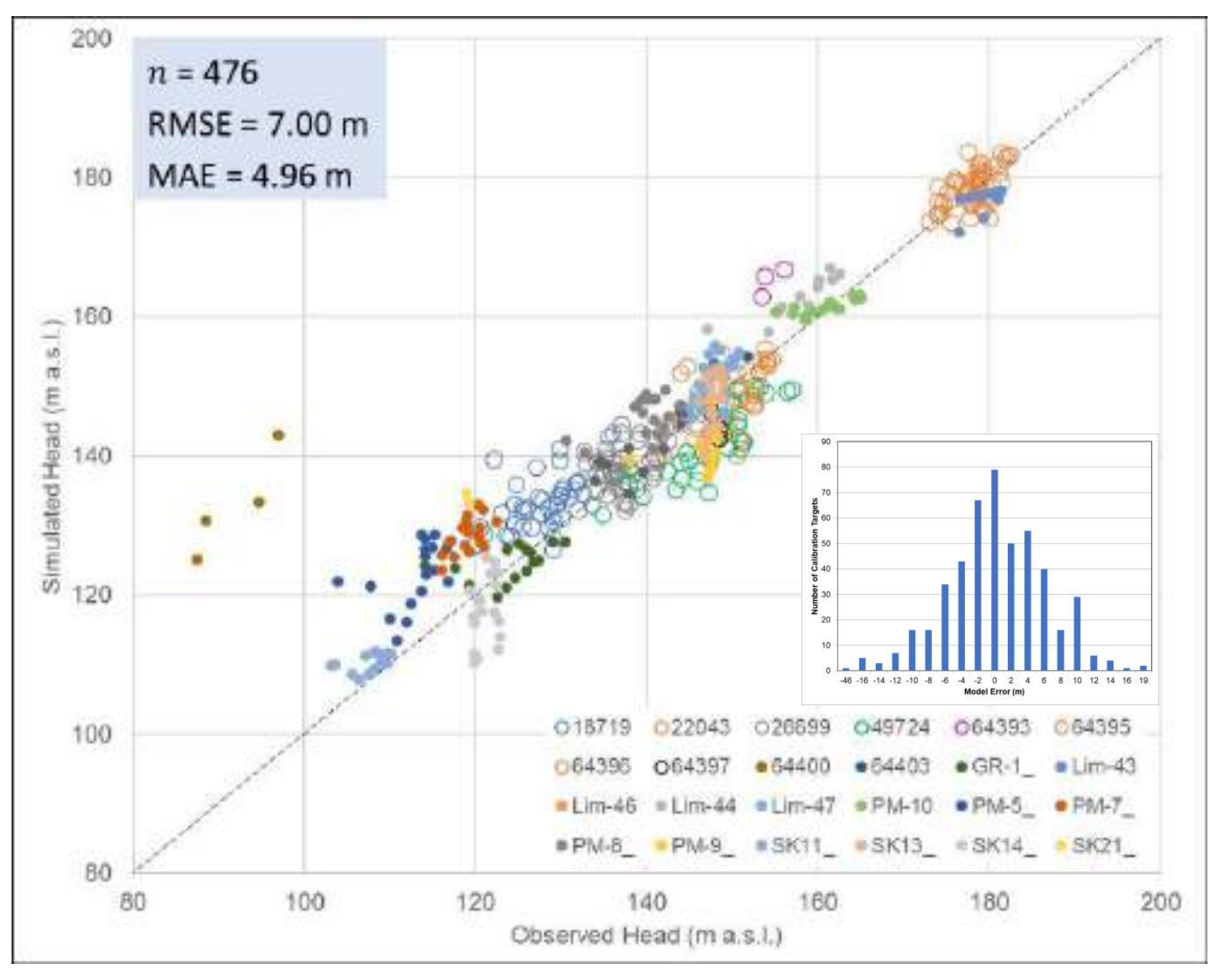


Fig. 8: Comparison of observed and simulated hydraulic heads (r^2=0.937) for calibration targets and histogram of model errors.

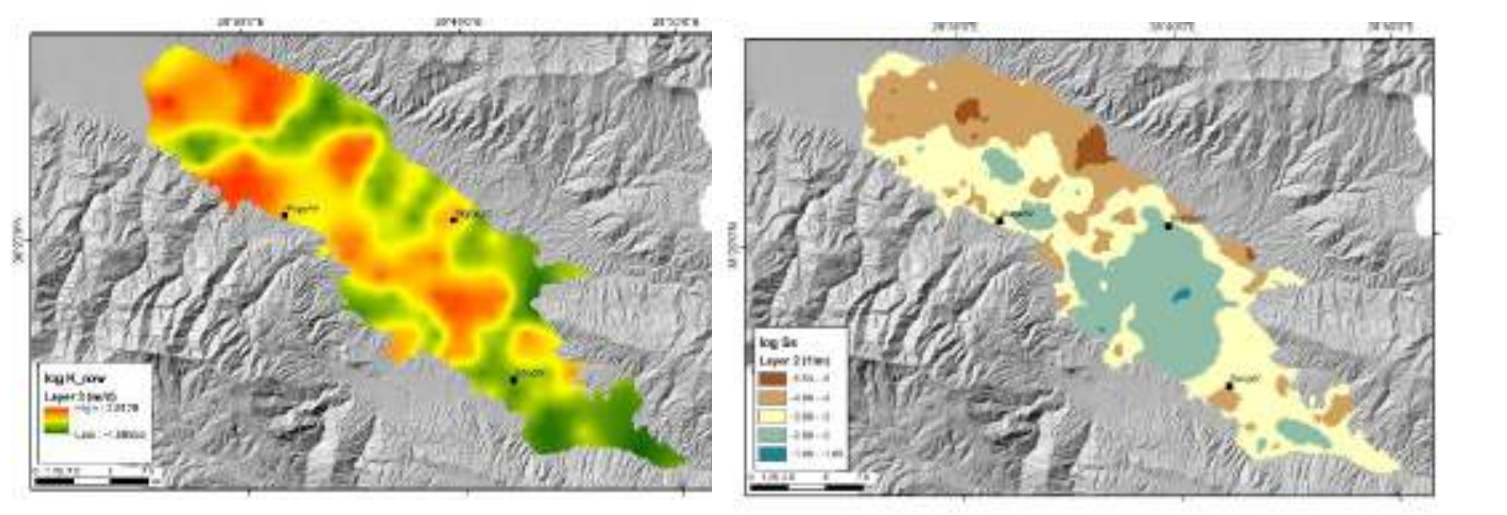


Fig. 9: Calibrated model parameters: horizontal hydraulic conductivity (left) and specific storage (right) fields.

Cumulative loss of groundwater = 74.34 Mm^3
Annual loss = 0.7509 Mm^3/yr

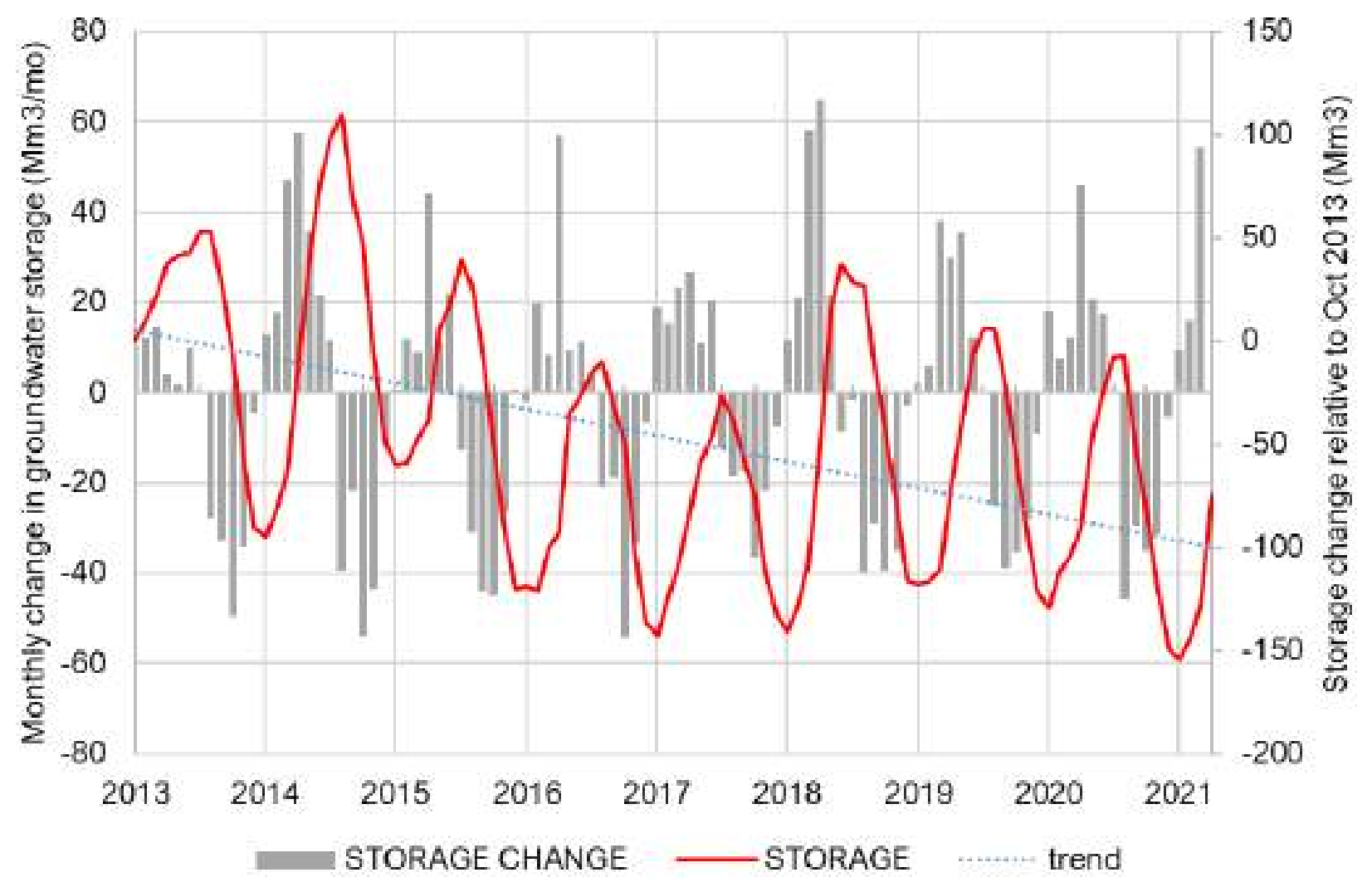


Fig. 10: Simulated groundwater storage change in the GRB alluvial aquifer relative to Oct 2013 and monthly storage differentials.

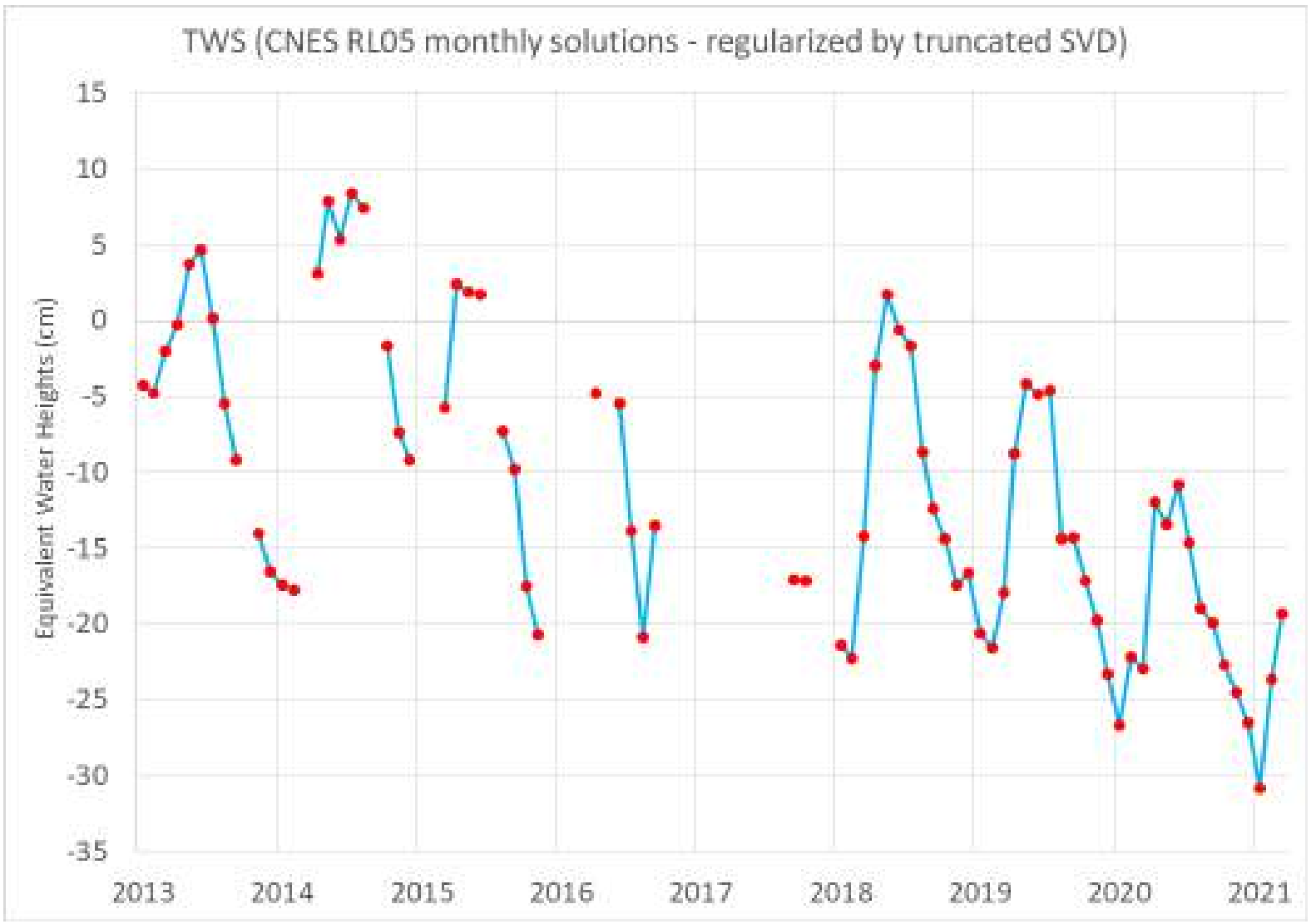


Fig. 11: GRACE equivalent water height of TWS for a point location in the study area expressed as anomaly with respect to reference period. Data obtained from GRACE solutions from CNES/GRGS.

Conclusions

- ❑ Comparison of MODFLOW groundwater storage solution and GRACE-derived TWS have **similar tendencies**, but further investigation needed to: **a)** obtain downscaled GRACE data; **b)** decompose groundwater storage from TWS signal
- ❑ **Satellite-based EO data** appears to be a **promising surrogate for in-situ observations** in the **calibration of groundwater flow models**. However, the use of EO data is conditional and product accuracy must be questioned.

Outlook & Recommendations

- ❑ Downscaled GRACE data is **indispensable** for hydrogeological modeling studies. Therefore, research on **developing downscaling methods must be encouraged**.
- ❑ **Data-driven analyses** and **machine learning** on groundwater related EO data archives and groundwater level measurements from piezometers at the regional scale can further **advance** the **usefulness** of hydrological EO data.

Acknowledgement

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