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Using data assimilation to improve land subsidence prediction from a data-driven and physics-based modeling approach: An application to Bangkok, Thailand

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Introduction

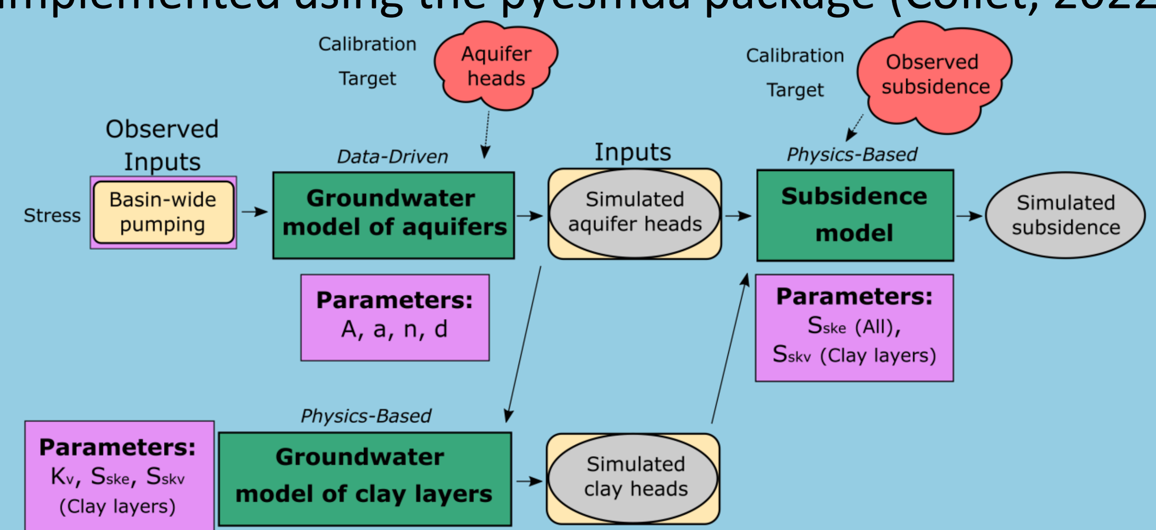
Subsidence is often caused by substantial groundwater pumping, especially in deltaic areas. Accurate subsidence simulation is greatly influenced by limited data availability, specifically input forcings/drivers and calibration data. In this study, an ensemble-based data-assimilation method is used to improve the estimates of land subsidence in Bangkok, Thailand, which is simulated by a linked data-driven and physics-based modeling approach. The approach is applied with limited groundwater and subsidence observations and only an estimate of basin-wide pumping. The assimilation of sparse and noisy head and subsidence observation data into the ESMDA algorithm results in improved estimates and uncertainty quantification of groundwater heads, localized groundwater pumping, and parameters.

Methods

Ensemble Smoother with Multiple Data Assimilation (ESMDA)

$$\mathbf{z}^a = \mathbf{z}^f + \mathbf{C}_{zz}\mathbf{H}^{\mathrm{T}}\left(\mathbf{H}\mathbf{C}_{zz}\,\mathbf{H}^{\mathrm{T}} + \alpha\,\mathbf{C}_{dd}\right)^{-1}\left(\mathbf{d}_{uc} - g(\mathbf{z}^f)\right)$$

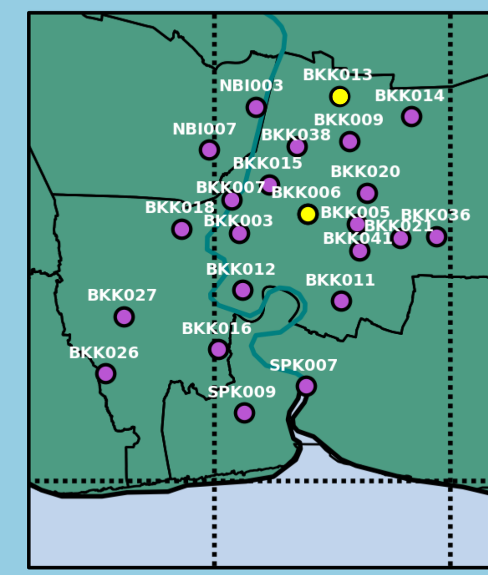
The update equation of ESMDA is based on Bayes' theorem, which combines prior knowledge and observations. Prior knowledge is represented through parameters and input (in purple boxes below) in **z** (state) and models (in green boxes) in g(). Observations added with error are represented by $\mathbf{d}_{uc}$. $\mathbf{C}_{zz}$ represents the state covariance matrix, and the $\mathbf{C}_{dd}$ observation error covariance matrix. α represents inflation factors that decreasingly overinflates the observation error for each ESMDA step. **H** is a matrix aligning parameters to observations. The update equation is applied for each ESMDA step. ESMDA is implemented using the pyesmda package (Collet, 2022).



A 3-step approach is developed to simulate land subsidence at observation well nests.

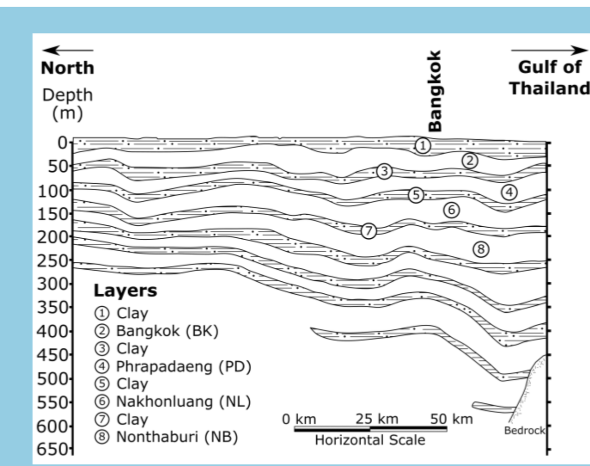
1. Heads in the aquifer at an observation well are simulated using a data-driven groundwater model called Pastas (Collenteur et al., 2019). Groundwater observations are assimilated using ESMDA in this step to estimate pumping rates and parameters for improved groundwater modeling.
2. These heads are used as the boundary conditions to simulate the heads in the clay layers using a physics-based groundwater model.
3. The heads in both the aquifer and clay layers are used as inputs to compute land subsidence at a given location through a physics-based elastoplastic subsidence model. Observed subsidence rates are assimilated using ESMDA in this step to estimate subsidence parameters for improved subsidence modeling.

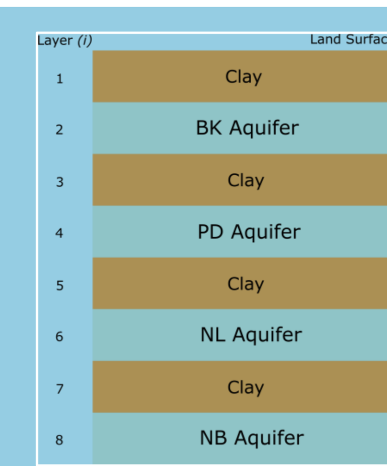
Study Site: Bangkok, Thailand



Far Left: The study area consists of the greater Bangkok region. The area denoted by the dashed purple box represents the area shown in other figures.

Left: The 23 observation well nests are located throughout the study area.





There are eight main aquifers beneath Bangkok, as shown on the cross section on the left. Only the four uppermost confined aquifers and their confining clay layers are considered (right).

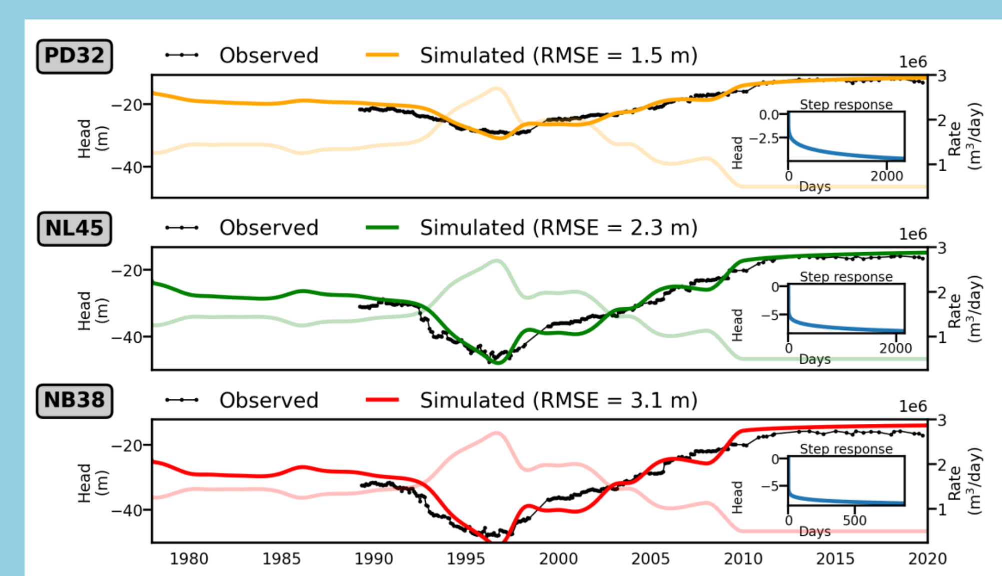
Results

a) ESMDA improves groundwater estimates and pumping rate time series.

Heads in the aquifer are simulated using time series analysis with response functions by having input time series explain observed heads in monitoring wells. For each model, the parameters of a time series model and pumping time series are estimated using ESMDA. The initial pumping time series estimate is a time series of basin-wide pumping rates. For each model, four parameters and pumping time series are estimated using four steps of ESMDA with an ensemble size of 500.

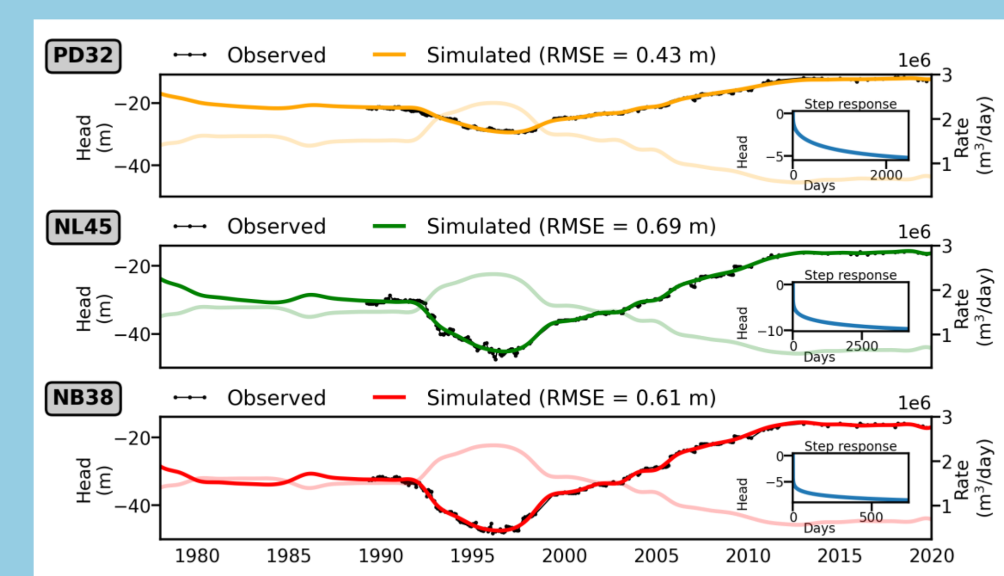
Well Nest BKK013

Basin-wide pumping rates used for every model



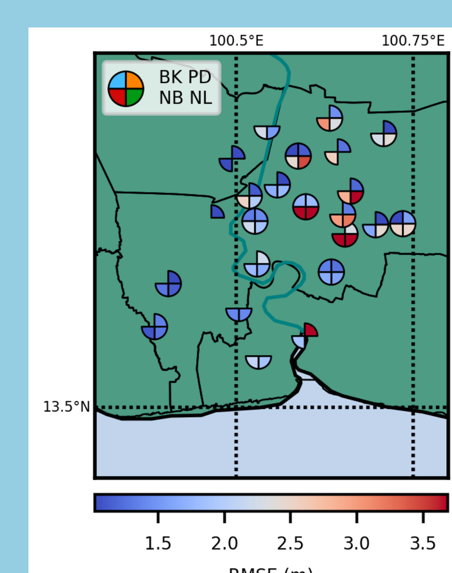
Results of time series models in well nest BKK013 for 1978-2020. Simulated heads for well PD32, well NL45, well NB38 in orange, green, and red, respectively, and observations (black) for each are plotted. The basin-wide pumping time series (faded orange, green, red lines, respectively) is the only input stress for these models.

Pumping rates with observed heads assimilated



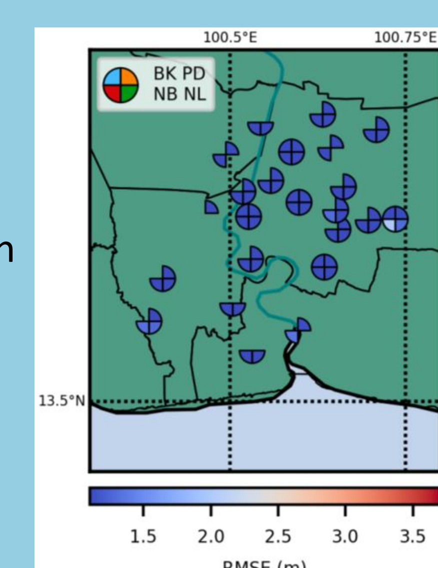
ESMDA estimates of localized pumping rates (faded orange, green, red lines, respectively) for this well nest using the basin-wide pumping time series as prior knowledge.

All Well Nests



The RMSE of the head for each well in a specific aquifer at each well nest when only basin-wide pumping rates are used.

The RMSE of the head for each well in a specific aquifer at each well nest when groundwater observations are assimilated using ESMDA.

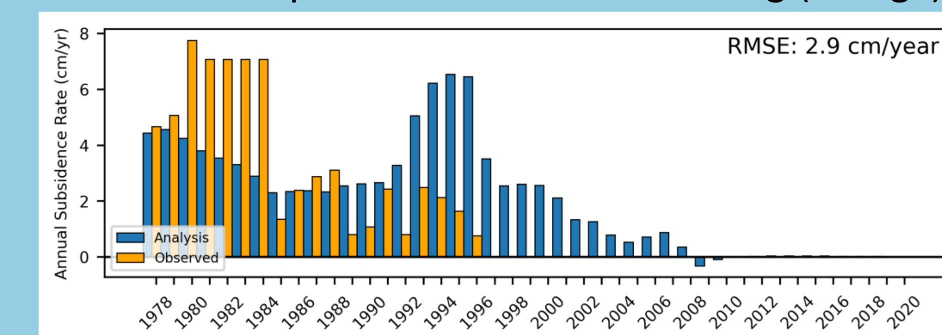


Results

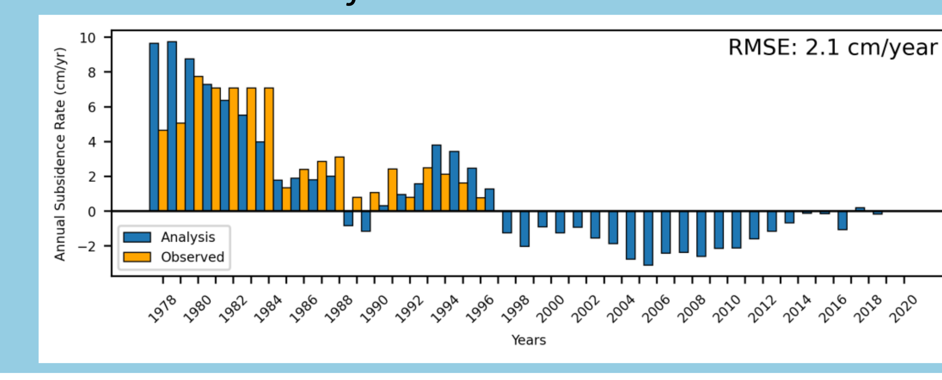
b) ESMDA constrains subsidence estimates.

The compaction of each layer is based on groundwater drawdown and layer properties. Land subsidence at a well nest is the sum of the compaction of all model layers. ESMDA is used to estimate three multiplier terms for each property and well nest.

Simulated (blue) annual rates of land subsidence at well nest BKK006 compared to benchmark leveling (orange).



Subsidence rates after observed subsidence assimilated



Conclusions

- This study demonstrates the capability of data assimilation to improve parameter and input estimation when simulating groundwater and subsidence and dealing with data scarcity.
- Groundwater: Average root mean square error (RMSE) of 2.0 m, prior to ESMDA. With ESMDA, an average RMSE of 0.6 m.
- Subsidence: RMSE of well nest BKK006 decreases from 2.9 to 2.1 cm/yr after implementing ESMDA.
- Future work: More work is needed in the ESMDA setup for parameter estimation of subsidence modeling to improve subsidence simulation.

Data Availability

Pastas:

Code and Data:

Acknowledgements

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Antoine Collet. (2022). pyESMDA - Python Ensemble Smoother with Multiple Data Assimilation (v0.3.2). Zenodo.