

Learning from satellite data: improve understanding of catchment processes through stepwise model hypothesis testing

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Learning from satellite data

From diagnosing deficiencies to formulating and testing alternative model hypotheses



Luangwa River Basin (Zambia)

159.000 km²

Mean precipitation ~ 970 mm yr⁻¹

Mean pot. evaporation ~ 1500 mm yr⁻¹

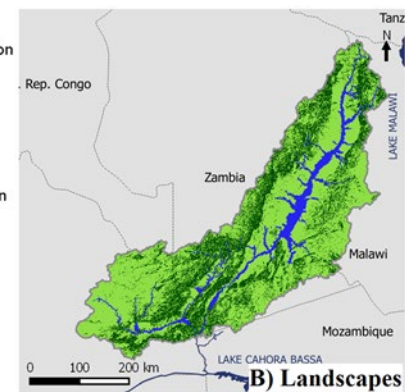
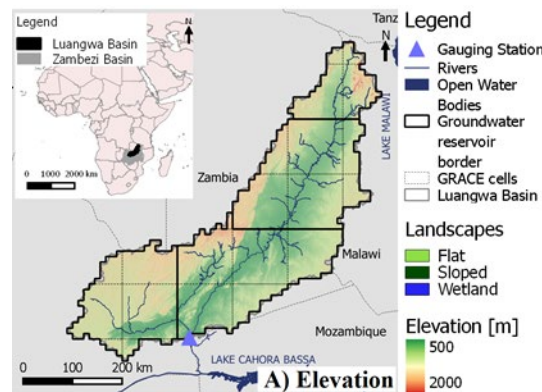
Savannah shrubland and deciduous forests



Hubert Savenije

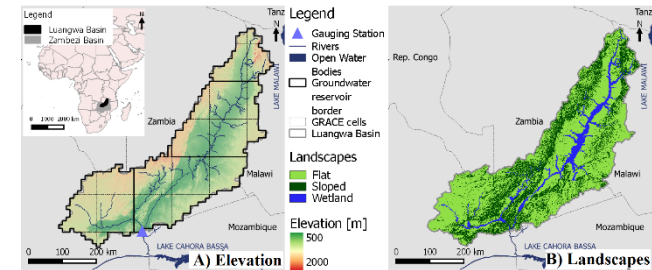
Research question:

Is there added value in using satellite data to calibrate, test and improve hydrological models?

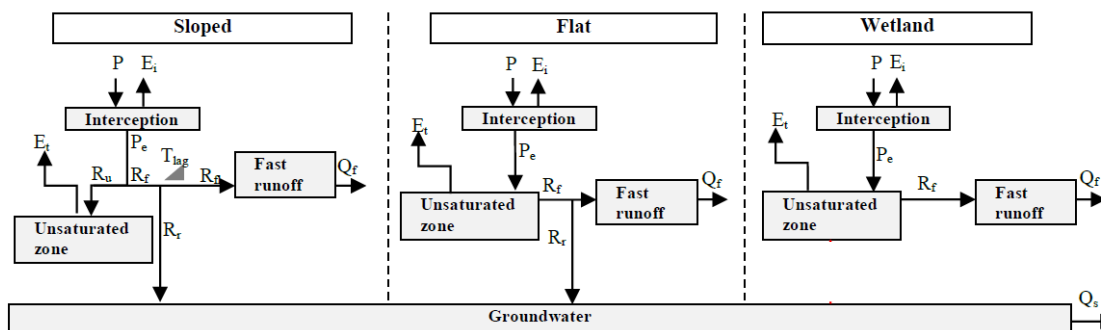


Benchmark Model A

How well does an off-the-shelf model do?



Distributed, process-based model and sub-grid stratification into 3 hydrological response units

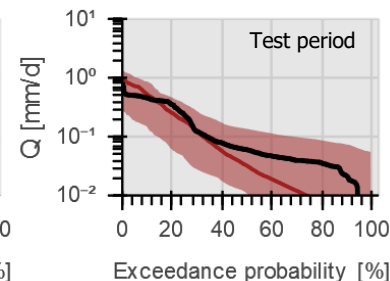
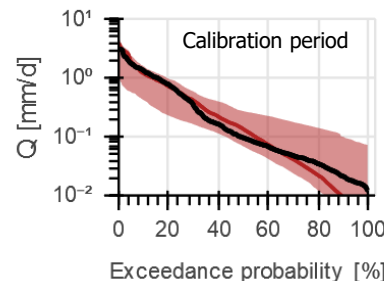
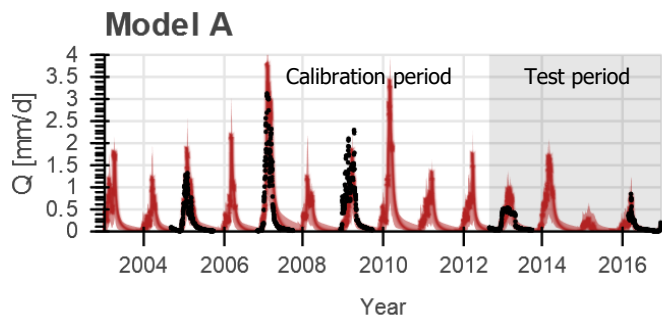


Model captures flow signatures well during calibration $D_E = 0.76$
In test period model exhibits performance reduction to $D_E = 0.37$

Multi-objective objective calibration 2003 – 2012
Train model to simultaneously reproduce eight hydrological signatures:

Calibration signatures
Time-series of flow
Time-series of logarithm of flow
Flow duration curve
Autocorrelation function of flow
Time-series dry season runoff coeff.
Time-series wet seasons runoff coeff.
Rising limb density of flow

Signatures combined in performance metric D_E
(Euclidean Distance; $D_E = 1$ perfect fit)

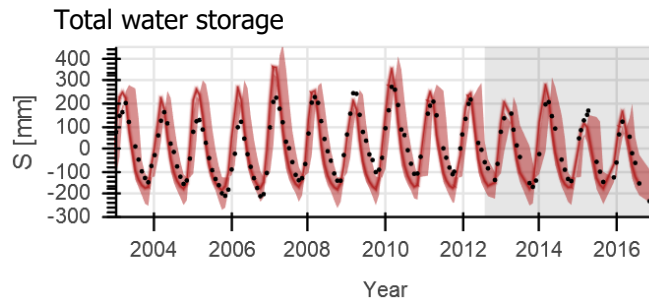
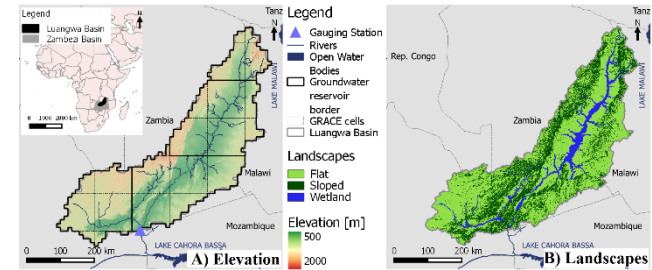


Hulsman et al., 2021 (HESS)

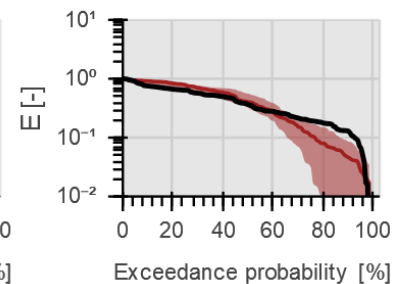
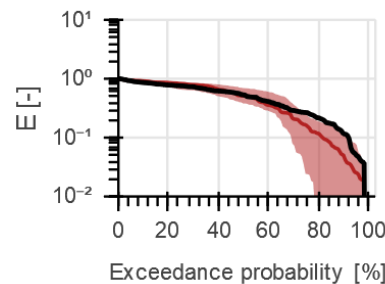
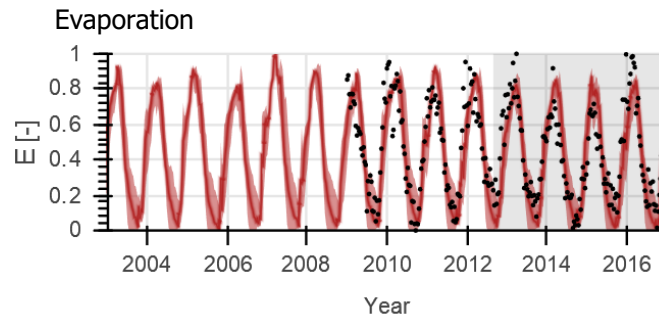
Benchmark Model A

How well does an off-the-shelf model do?

Evaluate the model's ability to reproduce the dynamics of remotely-sensed, basin-average total water storage fluctuations and evaporation.



Remote sensing data			
Total water storage	GRACE	monthly	2002 - 2016
Evaporation	WaPOR	10 days	2009 - 2016

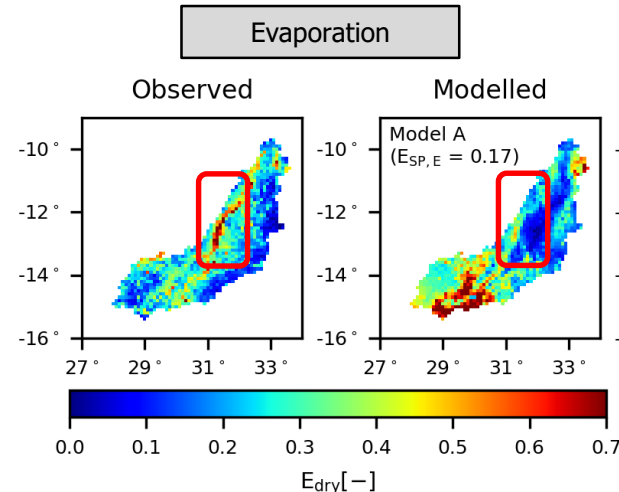
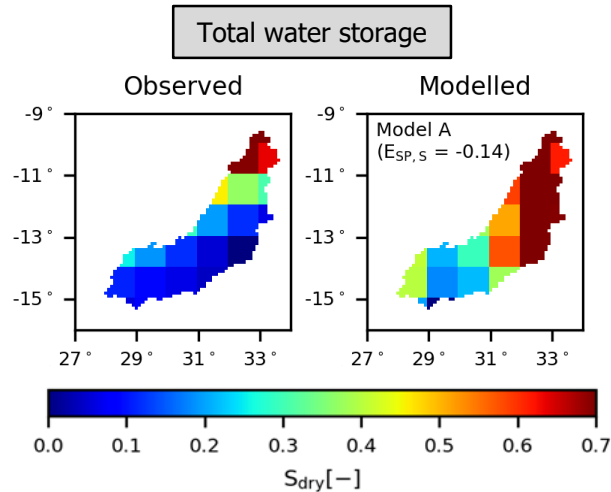
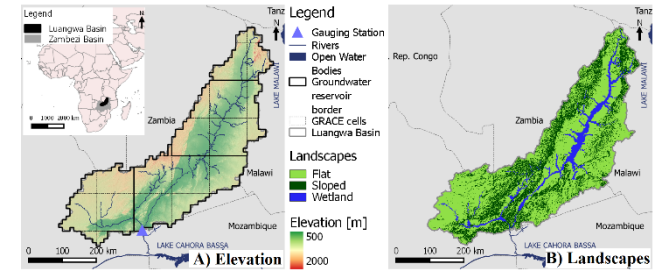


Model captures both, the dynamics of basin-average total water storage (Nash-Sutcliffe Efficiency $E_{NS,S} = 0.72$) and of basin-average evaporation ($E_{NS,E} = 0.57$), reasonably well

Hulsman et al., 2021 (HESS)

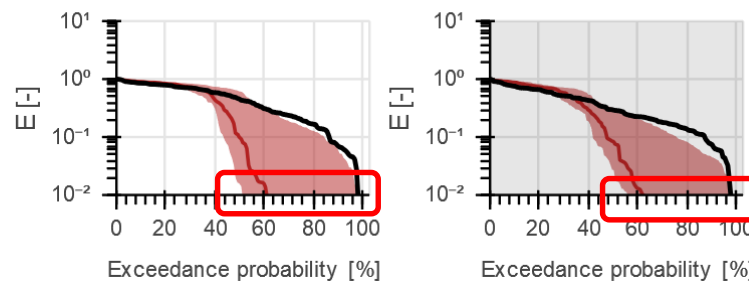
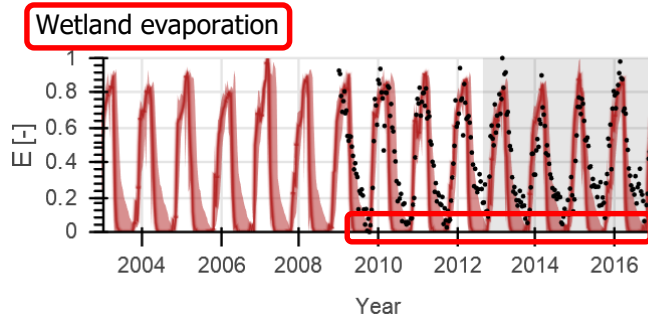
Benchmark Model A

Diagnosing model deficiencies



Model cannot reproduce the spatial pattern of time-averaged total water storage ($E_{SP,S} = -0.14$) and evaporation ($E_{SP,E} = 0.17$).

In particular, dry-season evaporation in wetland areas is considerably under-estimated by the model.

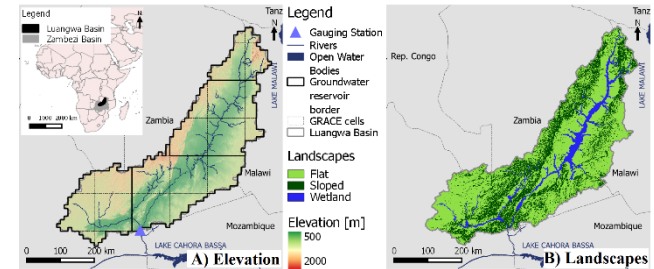


Modelled dry-season evaporation in wetlands is reduced to zero ($E_{NS,E,WL} = 0.27$). This contradicts the non-water limited conditions in wetlands

Hulsman et al., 2021 (HESS)

First model adaptation

Upwelling groundwater



Diagnosis:

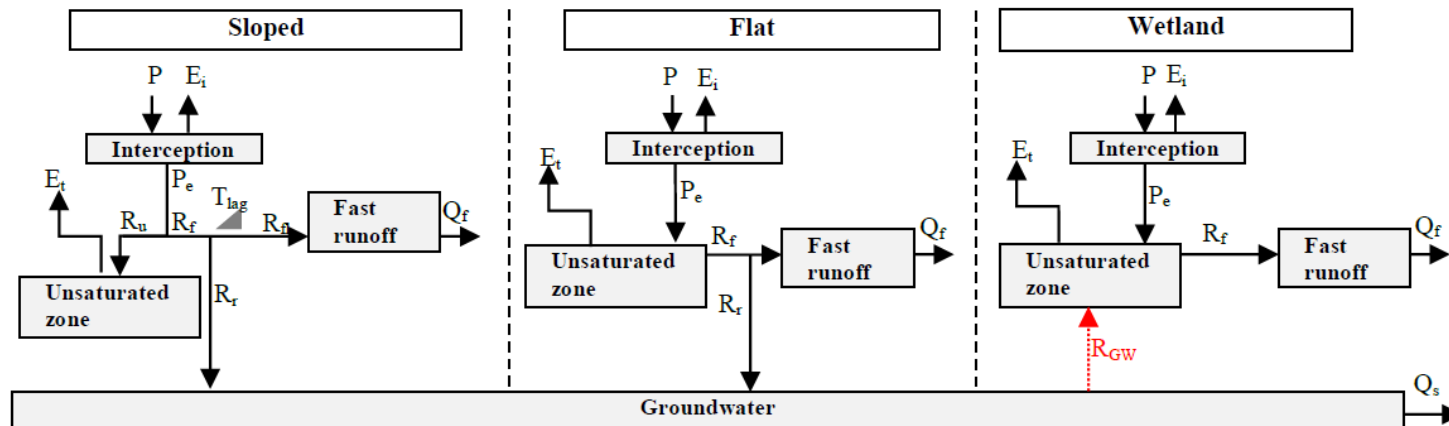
Modelled dry-season wetland evaporation is underestimated because the modelled unsaturated root zone in wetlands dries out during dry seasons.

Alternative hypothesis:

this happens because the model does not allow for groundwater from higher-elevation upland areas to well-up into the lower-elevation wetlands zones to sustain dry season evaporation.

Model adaptation:

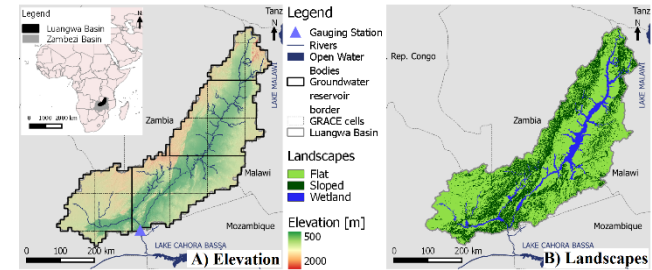
Allow **upwelling water flux** R_{GW} to replenish unsaturated root zone of wetlands, expressed as function of water storage in the groundwater model component.



Hulsman et al., 2021 (HESS)

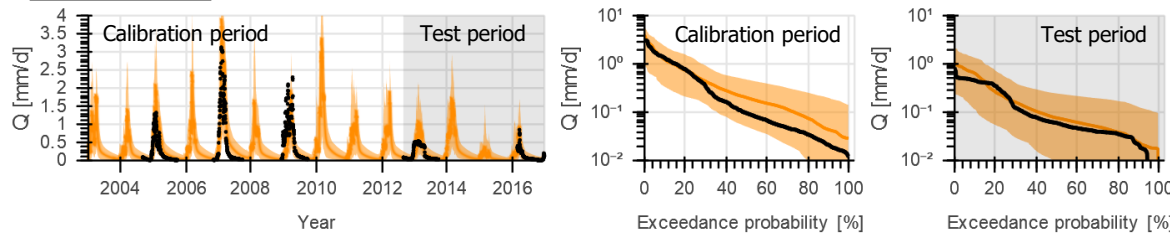
First model adaptation

Upwelling groundwater – Model C



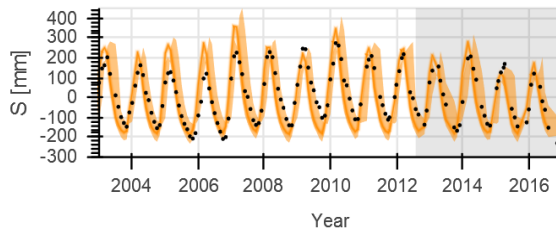
Model performance compared to **Model A**:

Stream flow



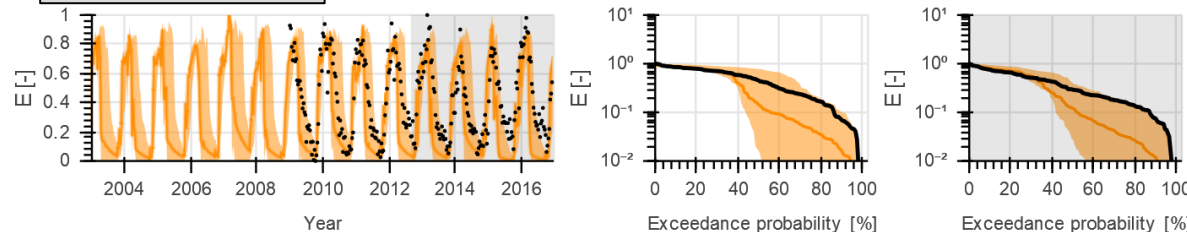
Model captures flow signatures slightly better during calibration $D_E = 0.79$. The test period model performance significantly improves to $D_E = 0.81$.

Basin-average total water storage



The model's ability to reproduce the dynamics of basin-average storage fluctuations remains stable at $E_{NS,S} = 0.70$

Wetland evaporation

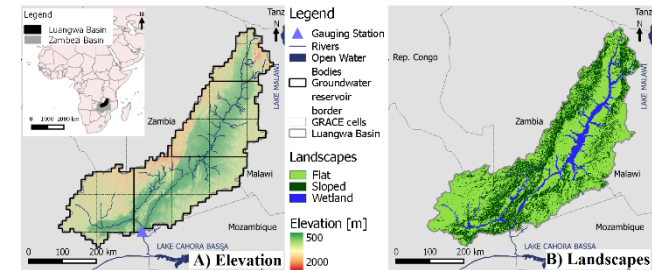


Modelled dry-season evaporation in wetlands remains above zero most of the time and thus better reflects the observed values ($E_{NS,E,WL} = 0.51$).

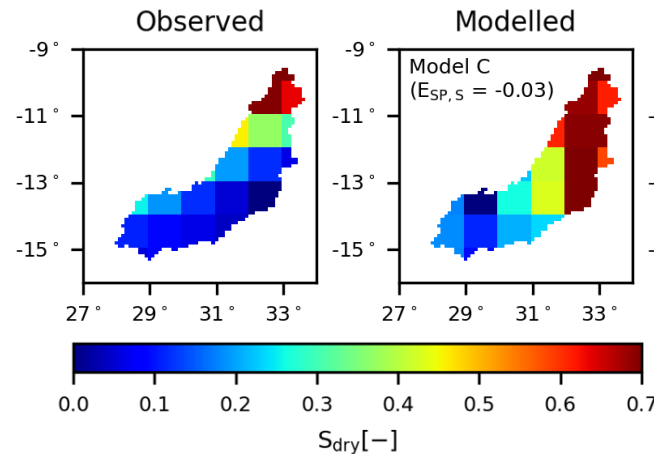
Hulsman et al., 2021 (HESS)

First model adaptation

Diagnosing model deficiencies – Model C

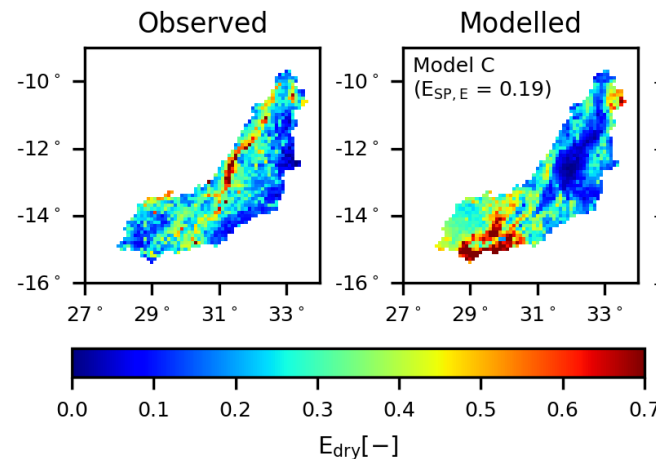


In spite of a significantly improved ability of the model to reproduce the hydrological response in the temporal domain, the model still struggles to provide a robust representation of the spatial pattern in water storage and evaporation



Model performance compared to **Model A**:

The model's ability to reproduce the dynamics of the time-averaged spatial pattern in total water storage fluctuations improves but remains at a low level of $E_{SP,S} = -0.03$

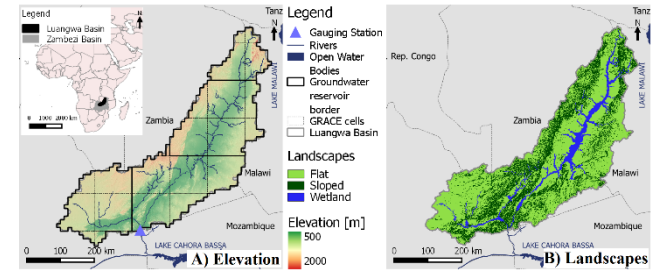


The model's ability to reproduce the dynamics of time-averaged evaporation remains rather stable at $E_{SP,E} = 0.19$

Hulsman et al., 2021 (HESS)

Second model adaptation

Increase spatial resolution of groundwater model component – Model F



Diagnosis:

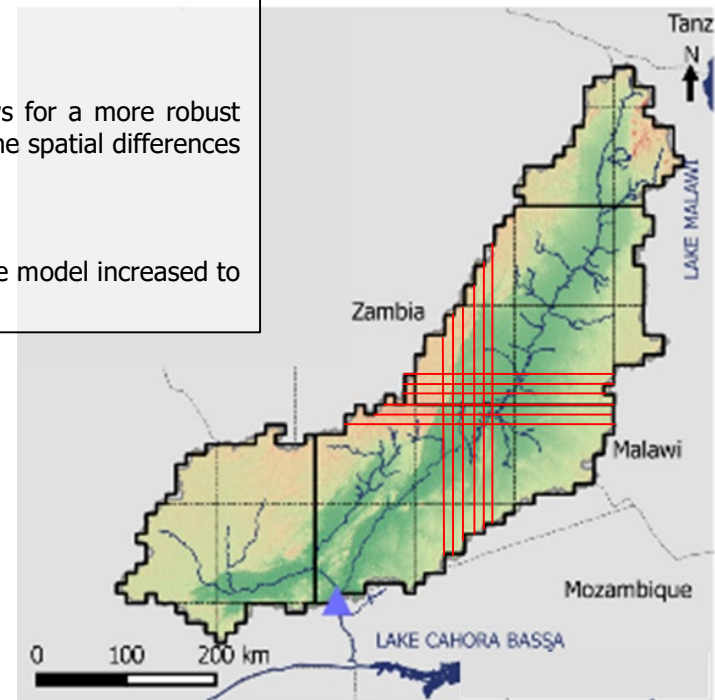
Spatial pattern of in particular total water storage fluctuations poorly captured by model, due to coarse spatial resolution of groundwater component in **Model A** and **Model C**, which prevents the representation of locally dissimilar groundwater fluctuations.

Alternative hypothesis:

Increasing the spatial resolution of the model groundwater component allows for a more robust representation of the local differences in total water storage, as it does filter the spatial differences in groundwater recharge to a lower degree.

Model adaptation:

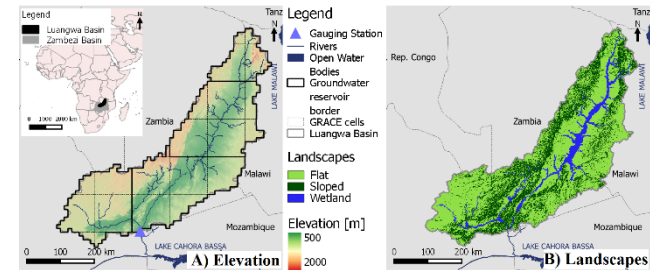
Using **Model C** as basis, the **spatial resolution** of groundwater component in the model increased to $10 \times 10 \text{ km}^2$, reflecting the spatial resolution of the precipitation input data.



Hulsman et al., 2021 (HESS)

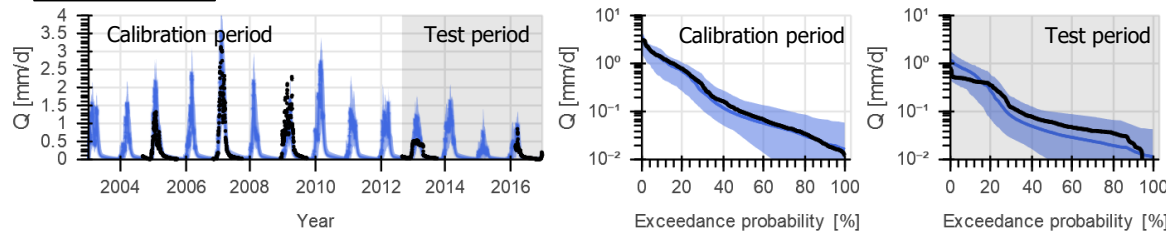
Second model adaptation

Increase spatial resolution of groundwater model component – Model F



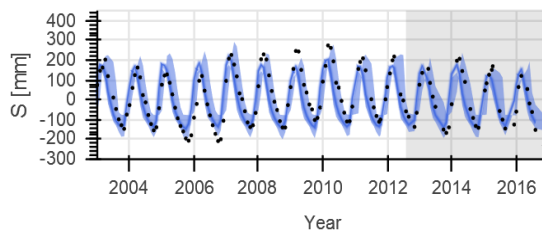
Model performance compared to **Model C**:

Stream flow



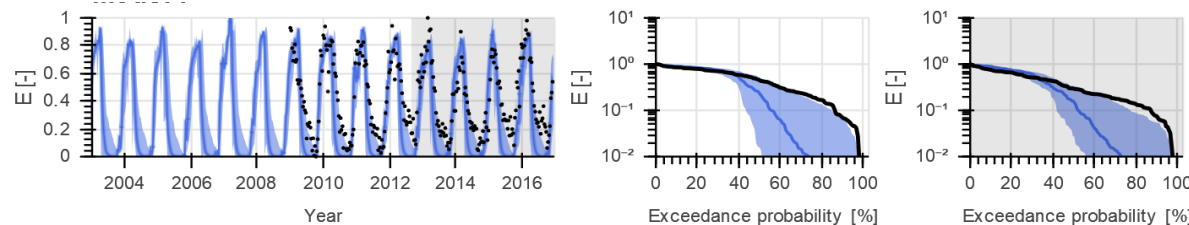
Model captures flow signatures extremely well during calibration $D_E = 0.91$. However, the test period model performance exhibits reductions to $D_E = 0.52$.

Basin-average total water storage



The model's ability to reproduce the dynamics of basin-average storage fluctuations slightly decreases(!) to $E_{NS,S} = 0.64$

Wetland evaporation



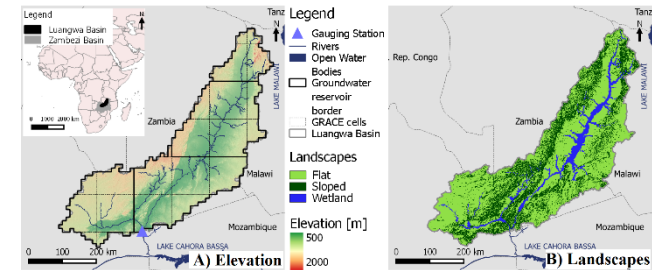
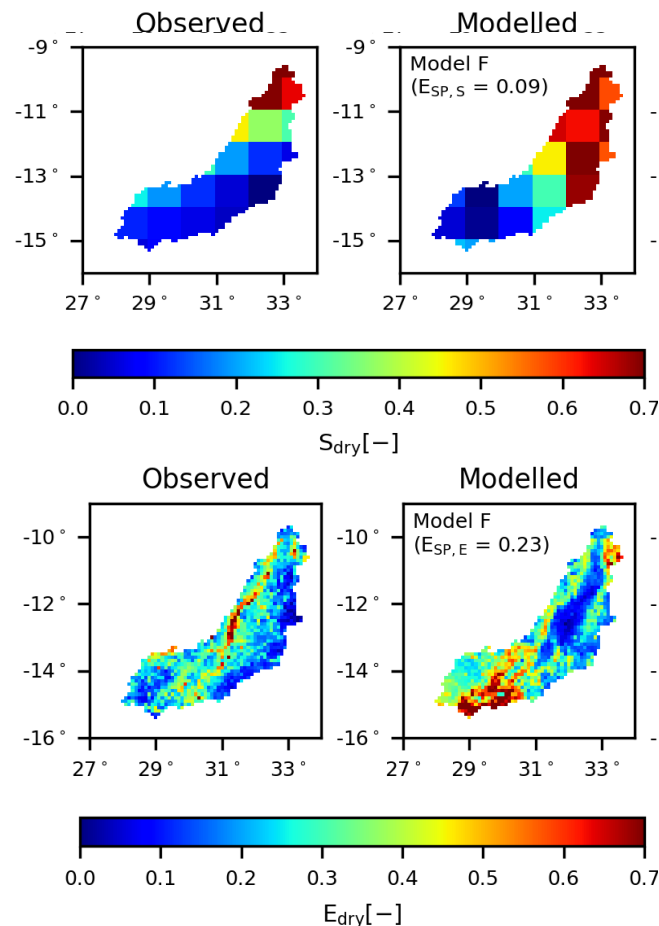
Modelled dry-season evaporation in wetlands remains above zero much of the time but is slightly reduced to $E_{NS,E,WL} = 0.45$.

Hulsman et al., 2021 (HESS)

Second model adaptation

Increase spatial resolution of groundwater model component – Model F

In spite of some improvements in the model's ability to reproduce the observed spatial pattern in total water storage and evaporation compared to **Model A** and **Model C**, the new **Model F** still struggles to provide a robust description of these spatial pattern.



Model performance compared to **Model C**:

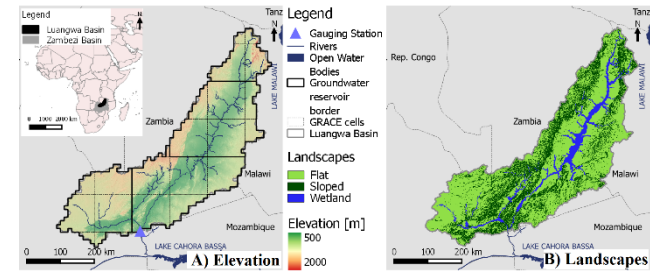
The model's ability to reproduce the dynamics of the time-averaged spatial pattern in total water storage fluctuations further improves but still remains at a rather low level of $E_{Sp,S} = 0.09$

Compared to **Model C**, the model's ability to reproduce the dynamics of time-averaged evaporation slightly improves to $E_{Sp,E} = 0.23$

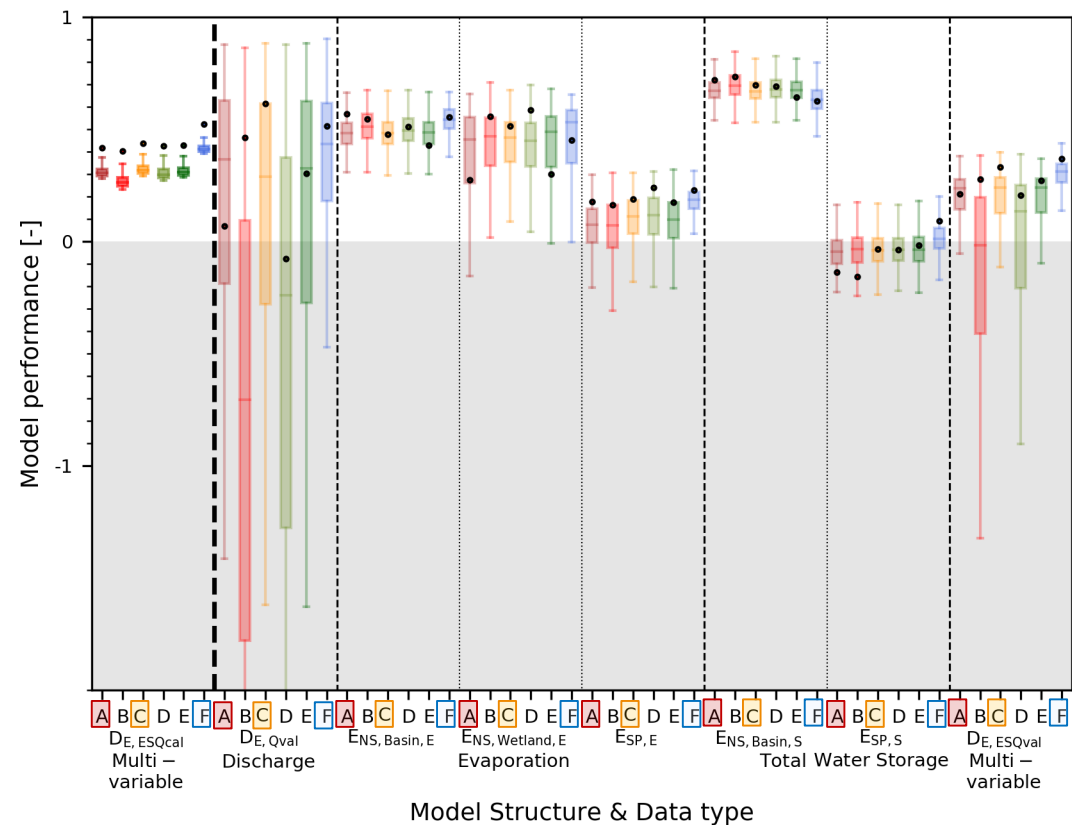
Hulsman et al., 2021 (HESS)

Take home message

Added value of remotely-sensed data for iterative mode improvement



- Good multi-objective stream flow calibration (**Model A**).
However Model A could neither well reproduce stream flow in test period, nor did it provide a meaningful representation of wetland evaporation and the general spatial pattern of evaporation and total water storage
- In a suite of model adaptations (Models B-F; here only **Model C** and **Model F** shown), no individual model could consistently improve all aspects of the response
- However, when calibrating and evaluating the model simultaneously to all temporal and spatial performance metrics, **Model F** provides overall the most robust representation of the system response. This is due to both, improved representation of stream flow (calibration & test periods), wetland evaporation, spatial pattern in evaporation as well as in total water storage.
- This highlights the limited information content of stream flow data for model calibration/evaluation and underlines the benefit of multiple temporal and spatial performance indicators for iterative model deficiency diagnosis and the associated model



Hulsman et al., 2021 (HESS)

Thank you!



Reference:
Hulsman, P., Savenije, H. H., & Hrachowitz, M. (2021). Learning from satellite observations: increased understanding of catchment processes through stepwise model improvement. *Hydrology and Earth System Sciences*, 25(2), 957-982.